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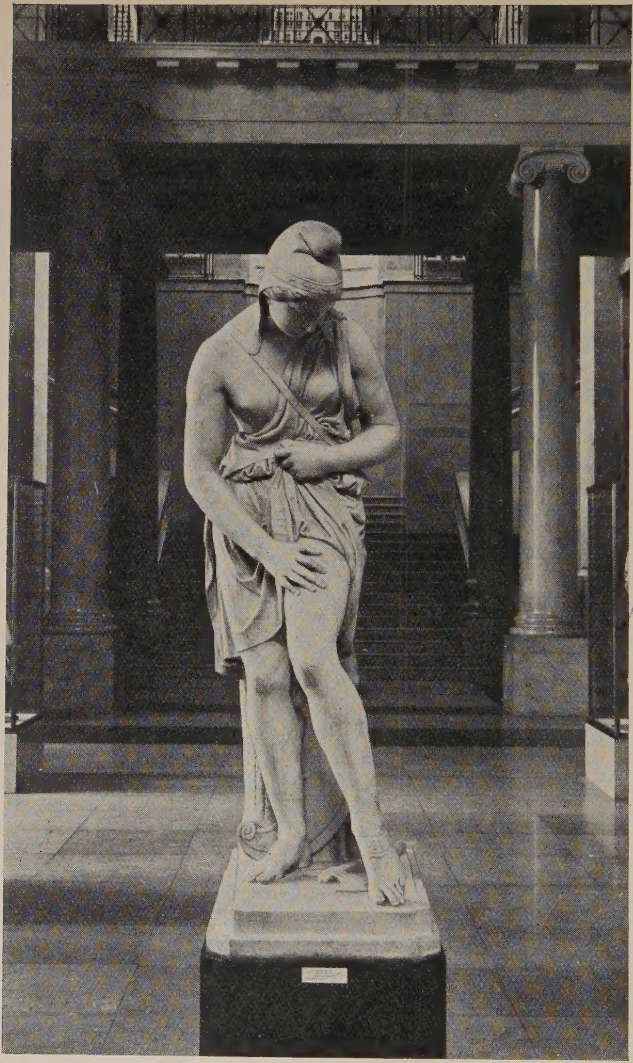

LIMESTONE IN ITS ÆSTHETIC AND UTILITARIAN APPLICATIONS.

Part of the interior of the entrance hall of the National Museum of Wales, a modern building constructed principally of limestone. The walls are of Portland Stone (see also Figs. 126 and 127), the stairways and floor of pale fossiliferous limestone from the Côte d'Or, associated with black Carboniferous Limestone from Belgium, while the Ionic columns are of Mazzano Marble from Italy, and the "Wounded Amazon," by John Gibson, R.A., illustrates the application of crystalline limestone in sculpture.

Frontispiece.

LIMESTONES

THEIR ORIGINS, DISTRIBUTION, AND USES

BY

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FOREWORD
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TO MY SCHOOLMASTER,
CYRUS H. HELLER, M.A.

PRINTED IN GREAT BRITAIN
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FOREWORD.

In the early days of the growth of scientific knowledge and its application in industry, pioneer workers were conspicuous for the breadth of their outlook and the variety of their interests. The chemist, for example, approached his work in the light of his knowledge of the physical properties of bodies, and the geologist was often equally well known for his chemical or biological studies, or for his engineering achievements. The actual amount of information available to the early investigators was comparatively small, but their experience was so comprehensive that they were able to recognise and enunciate the principles that have now become the fundamentals of modern scientific knowledge.

With the growth of knowledge, however, came the tendency to specialisation, and (although modern workers are no less able than their predecessors) as a result of close application to the study of one branch only of science or of industry, the extent of a man's information relating to one subject is often a measure of his ignorance of others, even of those cognate to that in which he has specialised. Instances of mistakes that have been made, and of opportunities that have been allowed to pass for want of wider knowledge and experience, are too well known to most of those into whose hands this book is likely to fall to need enumeration here—it is of greater importance to recognise their causes and to seek how they may be remedied.

The principal reasons for what may be called over-specialisation lie in the facts that (1) there is so much to consider in relation to each branch of science or of industry that a practical worker has little time to devote to other matters, and (2) the results of scientific and technical work are usually published in journals not readily accessible to the general reader, and they are, more often than not, expressed in terms that are unfamiliar to him. From the first of these two contributory factors there seems to be no escape, but the effects of the second can be appreciably lessened by the preparation of books which, although primarily devoted to one particular phase of science or industry, treat the subject in the light of work done in other fields of investigation the results of which proved to have a bearing—direct or indirect—upon the principal theme.

By this means, attention is drawn to matters that might otherwise be overlooked, and to research, already accomplished or in progress, that may have a bearing upon problems which from time to time arise: and, with adequate references to sources of information, such a work becomes, in effect, a guide to the literature of the subject in question.

The interest and importance of limestone, which is the subject of Dr. North's present book, are far greater than is generally known. Its economic importance may be judged from the facts that in Great Britain it constitutes about three-eighths of the whole of the stone quarried, and yields more than four-sevenths of the water obtained from wells and springs. It is used as a building stone, as a road stone, in making cement, lime, and mortar, in extracting iron and other metals from their ores, and in making glass, chemicals, soap, and artificial silk; indeed, directly or indirectly, it plays a part in nearly every phase of industry.

Among the features that contribute to its human and scientific interests are the facts that much of the characteristic scenery of our country owes its charm to the limestones that are so widely distributed therein, that successful agriculture is in large measure dependent upon limestone and its products, and that calcium carbonate, limestone's principal constituent, is, through the complex series of terrestrial and organic changes in which it is concerned, one of the fundamental necessities in the growth and development of all living things.

HENRY P. MAYBURY.

LONDON, 1930.

AUTHOR'S PREFACE

The subject-matter of this book was originally published as a series of articles (commenced in *The British Limemaster* and continued in *Cement, Lime and Gravel,* prepared at the suggestion of Mr. S. McPherson, Secretary of the Institute of Quarrying.

The literature relating to the geology, quarrying, and utilisation of limestone is scattered throughout the pages of many text-books, technical journals, and scientific "Proceedings," and it was felt that a general summary of the subject would serve a useful purpose. The language used is the simplest consistent with scientific accuracy, so that those concerned with the winning of limestone or with its utilisation may find explanations for some of the problems that arise from the nature of the material they use, its variations, its distribution, or its behaviour.

In the method of treatment and in the illustrations, the requirements of the student of geology have been taken into consideration, and the book is addressed also to the general reader, who may desire to know something of the building of the earth, of the origin of the materials that make up its crust, and of the way in which those materials have been pressed into the service of man.

The history of limestone, in its relation to the trend of civilisation, to the scenery and agriculture of our land, and to the determination and development of its industries, has been reviewed, in part because of its human interest, and in part because a knowledge of methods that have already been tried and of applications that have in the past been successful is always helpful.

References to sources of information have been freely introduced for the guidance of those desirous of entering into greater detail than proved to be possible in the present work, and also in order to indicate the authority for statements made concerning matters about which there may be differences of opinion. It is obviously impossible to include in a book of this description a complete bibliography of the subject, but the 400 or so references that are given, together with the additional references that those papers and books contain, should be sufficient to satisfy the needs of the most ardent enquirer.

Since animal remains figure so largely in the formation of limestone, an appendix dealing with the principles of the classification of the animal kingdom has been included, and a few fossils are represented among the illustrations, but readers who may not be familiar with the characters and nomenclature of fossil remains will find, in museums where geological specimens are adequately displayed, much of interest in connection with the formation of limestone.

It is with pleasure and gratitude that I make the following acknowledgments :—to Mr. McPherson, who, as Editor of the Journals previously mentioned, encouraged the use of illustrations on a lavish scale, to Messrs. F. F. Miskin, F.G.S., W. E. Howarth, F.G.S., I. Vaughan Evans, E. Neil Baynes, F.S.A., and others for the photographs from which have been reproduced the illustrations to which their initials or names are appended; to the Directors of the Geological Survey and of the Stone Preservation Committee of the Department of Scientific and Industrial Research, to the Controller of H.M. Stationery Office, the Council of the Geological Society of London, and others, for permission to reproduce the illustrations acknowledged in the appropriate places; to my colleague, Mr. H. A. Hyde, M.A., F.L.S., for suggestions relating to the chapter on agriculture; to my assistant, Miss N. E. Jackson, whose help has lightened the task of preparing this book for the Press, and to my colleague, Mr. W. E. Howarth, F.G.S., for preparing many of the diagrams and all the photographs of rocks and fossils : the specimens in question are in the geological collections of the National Museum of Wales, the Council of which I have to thank for permission to figure them, and also for permission to reproduce the Frontispiece and a number of illustrations that were originally prepared for geological monographs published by the Museum.

F. J. NORTH.

CARDIFF, 1930.

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PART I.

THE NATURE, ORIGIN, AND VARIETIES OF LIMESTONE.

CHAPTER I.

THE ORIGIN OF ROCKS IN GENERAL AND OF LIMESTONE IN PARTICULAR.

> "The aim and end of all geological work is not merely to tell us what rocks are like, but to enable us when we look at a rock to say how and where it was formed. When we can do this, Geology becomes not a mere catalogue of dry descriptions, but a history; and we learn to look upon rocks as the pages of a volume, in which is written an account of what was going on while they were being formed."
>
> A. H. GREEN in "*Physical Geology*" (1882).

Introduction.—The importance of limestone to the community, its interest to the student of earth-history, and its intimate association with man's pursuits and achievements have been indicated in the preceding pages, and they will be emphasised as successive aspects of its relation to science and industry are discussed.

In this country, limestone is very widely distributed and presents many variations in appearance, properties, and usefulness, and although the rock receives consideration in a large number of books and papers, there is no connected account of its geological history and economic applications: it is with the object of providing such an account that the present work has been undertaken.

All that has to be said concerning the distribution of limestone and the significance of its varieties can best be discussed in relation to its mode of origin, and, therefore, this part of the subject, which is in the nature of an introduction to the whole science of geology, will be dealt with in greater detail than might at first appear to be necessary. The advantage of following such a course will become increasingly apparent as we proceed.

It is interesting to note, in this connection, that the earliest paper written in this country upon what we should now describe as a geological subject, relates largely to limestone. George Owen, a Pembrokeshire man who lived during the time of Queen Elizabeth, left many manuscripts relating to the history and natural features of his native county; and one of them, dated 1595, describes the distribution of limestone in South Wales and its use in preparing lime for agricultural purposes. The substance of the paper was afterwards incorporated in his *Description of Penbrookshire in generall,* which is dated 1603.

He described the distribution in Pembrokeshire of the rock now known as the Carboniferous Limestone, and, in discussing its relation to similar rocks in other parts of South Wales, showed a familiarity with its outcrop, remarkable in view of the difficulties of travel at that time. Owen considered it a matter of importance to trace the course of the limestone, partly because the material was in great demand for lime-burning, and partly because he realised the relation which exists between it and other rocks, such as coal. He wrote :—

> " This digression concerning these two vaynes of lymestones taking their originalle here in *Penbrokshire*, I have thought good to Insert in this place, for . . . beinge noted and knowne yt may be a guide to some partes to seake the lymestone, whereas yett it lyeth hid, and may save labour to others in seakinge it where there is noe possibillitie to finde it."

Limestone considered as a constituent of the earth's crust.—Limestone is a rock, and as such, its origin can only be satisfactorily discussed in relation to the origin of rocks in general. According to their mode of origin, rocks may be divided into three main classes :—

1. Sedimentary rocks are those which, like sandstone and clay, originated as sediments, derived from the disintegration of previously existing rocks, transported by water or wind, and deposited in lakes or in ocean basins, or spread over the surface of the land. For present purposes we may also include with them, rocks consisting, like coal and limestone, largely or entirely of material produced by the activities of plants or animals, and also certain rocks that originated as material precipitated from water by chemical or bacterial action.

2. Igneous rocks, so named from a Latin word, meaning fire, are those which, like granite and basalt, were at one time

in a molten condition, and which cooled either within the earth's crust or upon its surface (*Fig.* 1).

3. Metamorphic rocks, so named from Greek words meaning a change of form, are sedimentary or igneous rocks which, as a result of the action of heat, chemical change, or pressure, have been more or less completely altered in texture and probably also in mineralogical composition, so that their original characters are obscured or even obliterated: schist, slate, and marble may be mentioned as examples of metamorphic rocks.

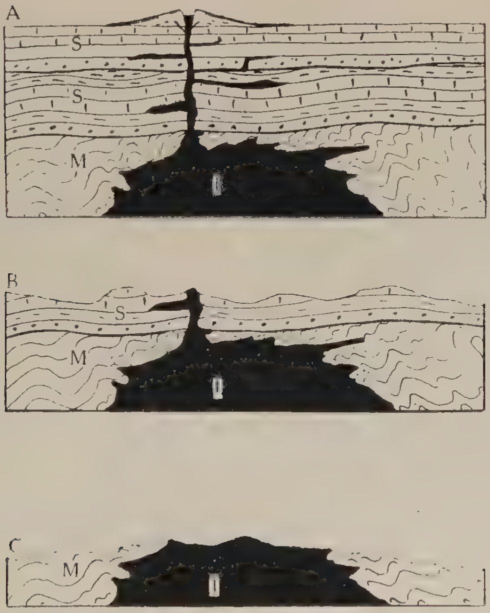

FIG. 1. — DIAGRAMS ILLUSTRATING THE STRUCTURE OF THE EARTH'S CRUST.

A, illustrates diagrammatically the relation between sedimentary rocks (S), igneous rocks (I), and metamorphic rocks (M), and B and C show how, by denudation, the once deeply buried igneous and metamorphic rocks may be exposed at the surface.

Sedimentary Rocks. Limestone (except for the crystalline marbles which are metamorphic) is a sedimentary rock, and it is therefore of those rocks alone that a detailed discussion is necessary in the present work.

Wherever rocks are exposed at the surface of the earth they are being disintegrated and decomposed, although the forces engaged in this work differ in different places. In temperate regions, rain and the acids dissolved in it are the chief causes of rock weathering; in cold regions, and at high altitudes in temperate regions, the shattering action of frost predominates; in rainless regions, rocks are disintegrated by the mechanical stresses due to the extremes of heat and cold so characteristic of deserts, and their broken fragments are shifted by the wind; along the seashore, rocks are slowly worn away under the buffeting of the waves and the stones which they hurl against the cliffs (*Fig.* 2), whilst the beach pebbles, constantly on the move as the tide flows and ebbs, grind one another away forming sand and mud (*Fig.* 3).

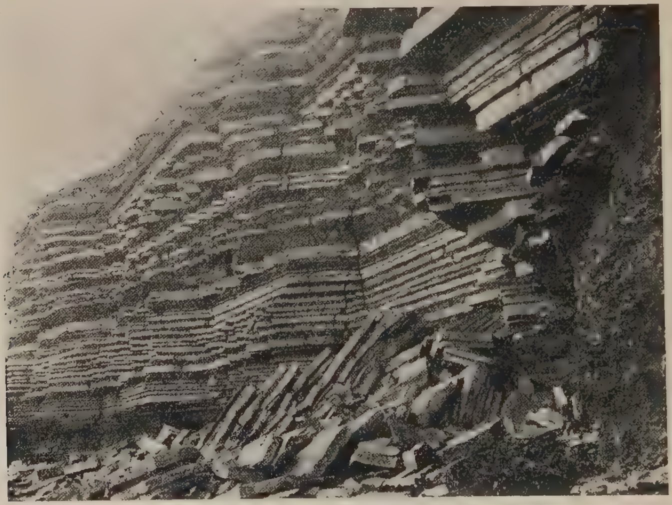

FIG. 2.—LIMESTONES AND SHALES OF THE LOWER LIAS AT LAVERNOCK, GLAMORGAN.

The strata are practically horizontal, and the photograph illustrates the way in which bedding planes and joints facilitate the destruction of rocks along the sea shore. (*Photo F.F.M.*)

Under normal conditions the weathering of rocks involves their mechanical disintegration, as well as the chemical alteration of some of their constituent minerals. Many minerals are decomposed by rain-water charged with the gases (among which is carbon dioxide) which it dissolves during its passage through the air, and give rise to comparatively soft incoherent material that is easily washed away by rain or blown away by wind: when the products of chemical change have been removed, the remaining undecomposed particles are no longer held securely together, and they, too, are liable to be blown or washed away. This removal of material from the surface of the earth, and the consequent exposure of fresh material to the same destructive influences, is known as "denudation."

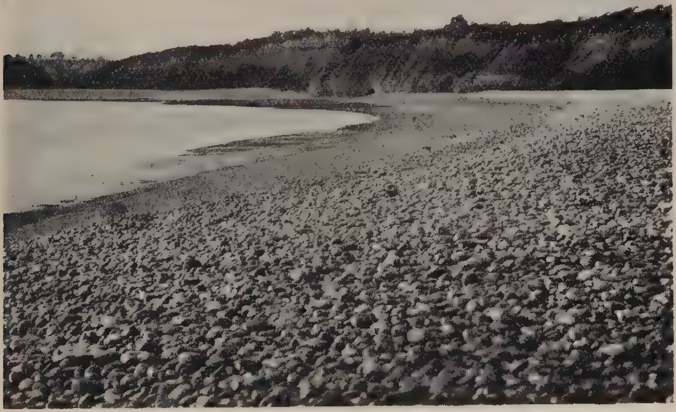

FIG. 3.—A BEACH OF LIMESTONE PEBBLES AT BARRY, GLAMORGAN.

The pebbles have been produced by the action of the waves upon fragments of rock derived from the distant cliffs.

Sooner or later, most of the disintegrated material produced on the surface of the land as a result of atmospheric weathering finds its way (by the action of rain, wind, or gravity) into streams, and by them is carried along until it eventually comes to rest upon the floor of the sea into which the stream discharges. Here, also, accumulates the material produced by the destructive action of the waves upon the rocks of the coast.

During its transport by streams and its distribution on the sea floor, the material derived from the destruction of rocks on land or along the coast tends to be sorted out according to size, because, other conditions being equal, small particles would naturally be carried farther and more quickly than the larger ones (*Fig.* 4). Therefore, the sediments will tend to decrease in size seawards—the coarse material (pebbles and gravel) being

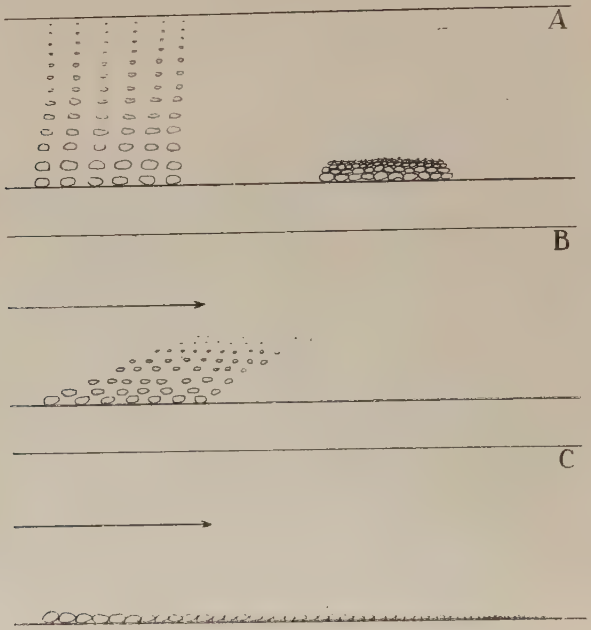

FIG. 4.—DIAGRAM ILLUSTRATING THE SORTING OF SEDIMENTS.

In still water, particles tend to subside according to size, the largest falling most rapidly as in A; in moving water, the smaller particles, falling more slowly, travel a greater distance before they settle down, as in B and C; thus, in rivers, owing to the flow of the stream, or along the sea shore owing to the action of the waves, rock particles tend to be sorted out according to size.

deposited near the coast, followed by the finer material (sand), while beyond that, the finest particles resulting from the decomposition of rocks will form mud; see *Figs.* 3 and 5.

When subsequent geographical changes, to be referred to hereafter, cause a sea floor of one age to become a land area of another, the accumulated sediments will constitute the rocks of the new land—the pebbles will give rise to the rocks known as conglomerates, the sand to sandstones, and the mud to clay or shale. The processes by which soft and incoherent sediments have become hard rocks will be discussed at a later stage.

During the decomposition of rocks some of their ingredients are carried away, not as solid particles, but in solution, with the result that river waters contain varying, but usually small, quantities of inorganic substances such as calcium carbonate (carbonate of lime), calcium sulphate, common salt (sodium chloride), and compounds of magnesium and iron. Interesting evidence relating to the amount of material transported in this way was obtained in connection with the Royal Commission on Water Supply, appointed in 1867 [1, 2].* It was found that

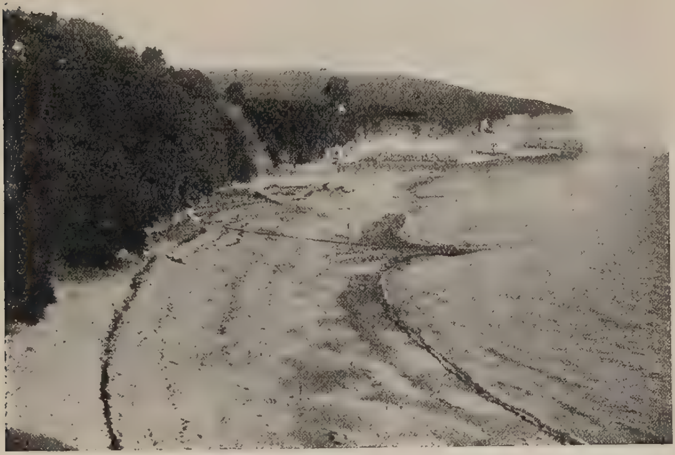

FIG. 5.—CLIFF AND BEACH AT ST. MARY'S WELL BAY, GLAMORGAN.

A beach of water-worn pebbles passes gradually into a stretch of sand. The distant cliff, consisting of limestone and shale (Lavernock Point), is undergoing constant erosion, but the beach protects from destruction the cliffs on the left that are, in consequence, covered with vegetation. (*Photo F.F.M.*)

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* Numbers in square brackets refer to the books or papers enumerated in the Lists of References given at the end of each chapter. Each separate list commences with No. 1 and relates to the subject matter of the chapter in question: it is believed that such an arrangement will be more convenient than a general Bibliography at the end of the book.

the average quantity of dissolved material carried down by the Thames past Kingston was 548,230 tons per annum, of which about two-thirds was calcium carbonate: this represents the removal in solution of about 140 tons from every square mile of chalk exposed in the drainage area involved.

Soluble materials are also taken into the water during the process of wearing away the rocks of the sea coast, and, when all the solid particles brought down by the rivers, or derived from the waste of the cliffs, have settled out upon the sea floor, the dissolved substances still remain, and some of these, such as common salt, are in all probability gradually becoming more abundant in sea water, as the table above (*Fig.* 6) indicates.

	Dee, near Aberdeen	*Rhine, near Basle*	*Thames, near Ditton*	*Seine, near Paris*	*Sea water (average)*
Calcium carbonate ...	1.22	12.79	16.84	17.4	12.18
Calcium sulphate ..	0.17	1.54	4.37	3.9	126.00
Magnesium carbonate .	0.20	1.35	1.81	6.2	?
Magnesium sulphate Magnesium chloride and magnesium bromide	0.46	0.39	—	1.7	554.12
Sodium chloride ..	0.96	0.15	1.57	2.5	2721.43
Other substances (silica, iron, potassium salts, etc.) ..	0.11	0.9	2.61	1.4	86.27
TOTAL	3.12	17.12	27.20	33.1	3500.00

FIG. 6.—TABLE SHOWING SUBSTANCES DISSOLVED IN RIVER WATER AND SEA WATER.

The figures quoted are parts per 100,000: it will be noticed that rivers, which, like the Dee, flow over hard rocks such as granite and slate, carry very little dissolved material in comparison with rivers like the Thames, that flow over clays and soft calcareous rocks such as chalk.

Some of the dissolved material is utilised by various kinds of animals and plants which are able to abstract it from the water and incorporate it into their shells, skeletons, or other supporting structures.* Fishes use it to harden their bones, and crabs their outer skins; while other creatures like mussels, oysters, and winkles, build for themselves shells of it.

The comparatively small amount of calcium carbonate in sea water may be, in part, due to the action of lime-secreting organisms, but it has been suggested that since calcium carbonate is so slightly soluble, the available amount of that substance in solution is not sufficient to account for the vast deposits of calcareous material of organic origin that have been formed or are still in process of accumulation. Sir John Murray, in collaboration with R. Irvine, proved experimentally that certain marine creatures could build skeletal structures of calcium carbonate when living in sea water from which that substance was excluded, although calcium sulphate was present; from this it was inferred that in such cases the calcium carbonate resulted from the interaction of ammonium carbonate, produced in the tissues and the secretions of the animals, with the calcium sulphate that was dissolved in the water [2a].

Whatever the nature of the process involved, the shells and skeletons of marine animals consist principally of calcium carbonate, and when the animals die, and the flesh decays or is eaten by some other animal, the shells and the bones fall to the bottom and mingle with the sediment that is accumulating there. For this reason, clays, shales, and sandstones frequently contain shells and other hard parts of animals—fossils, as they are called—and, as the distance from the source of the land-derived material increases and the sediment becomes less in quantity, the calcareous matter will increase in proportion until it makes up practically the whole of the deposit. The result is that, if no ordinary sediments are being deposited (either on account of the distance from the land, or because for some reason or other very little solid material is being discharged into the sea), the whole of the deposit accumulating upon the sea floor will consist of the hard parts of animals, either entire, or in a broken condition; this material may eventually give rise to a fourth kind of rock—limestone.

When a river reaches the sea, the velocity of its water is checked, and if the water is carrying an excessive quantity of mud, it will be deposited near the mouth of the river, choking the estuary and perhaps forming a delta, so that in addition to the clay rocks which originated from mud deposited far out to sea, there are others derived from material deposited as mud-banks in estuaries or in deltas. The mode of origin of a clay can usually be determined by the fossils it contains: the shells present in a marine clay will be those of animals that normally live in the sea, whilst those in clays of estuarine origin will have belonged to creatures that frequent fresh or brackish waters.

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* For example, the composition of an oyster shell is as follows:—Calcium carbonate, 93·9%, magnesium carbonate, 0.3%, calcium phosphate, 0.5%, calcium sulphate, 1.4%, organic matter 3·9%.

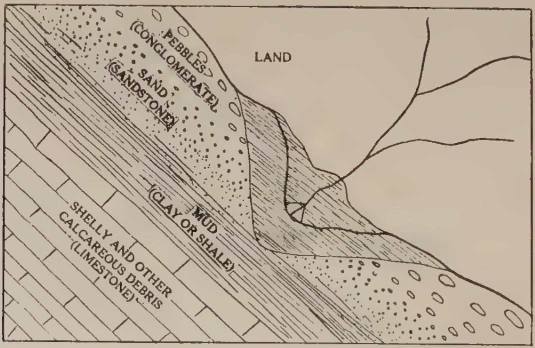

FIG. 7.—Diagrammatic representation of the arrangement of sediments on the sea floor.

The sediments have been derived from a land mass on the right, and are represented on the left as spread on the sea floor. The diagram indicates only the general arrangement according to the size of the particles and the distance from land; in actual fact the belts of sediment would be less regularly arranged on account of differences in the supply of material from rivers or cliffs undergoing erosion.

The four principal kinds of sediment—pebbles, sand, mud, and the calcareous material which, when subsequently consolidated, becomes limestone—will, therefore, be spread on the sea floor in tracts more or less parallel to the shore — the pebbles in the shallowest water and the limestone farthest from land (*Fig.* 7). The passage from one kind of sediment into another will not be sharp, for, by an increase in the amount of muddy material, a sandy deposit (which will eventually form sandstone) may pass into argillaceous (that is, clayey) sand, and eventually into mud (which will give rise to clay or shale). In the same way, as calcareous (limy) matter becomes more abundant, a sand may pass into calcareous sand, or a mud into calcareous mud that will eventually form a marl, and, with still further increase in the proportion of calcareous matter the deposit will become a sandy limestone or an argillaceous limestone.

Other deposits that may give rise to limestone are accumulations of shells in shallow water, shell banks formed along the sea shore, and the debris of coral reefs.

A knowledge of their mode of accumulation makes it possible to understand the passage of one kind of rock into another, as for example the change seen in the Carboniferous Limestone as one passes northward from Derbyshire.* At first it is a massive limestone formation, but when traced along the Pennine Chain it becomes broken up by beds of shale and sandstone which increase in thickness and abundance until, in Northumberland, the formation is represented by a group of sandstones and shales with a few subordinate beds of limestone; see *Fig.* 8. In a similar way the lower part of the Chalk becomes a calcareous sandstone when traced from the south-east of England into Devonshire.

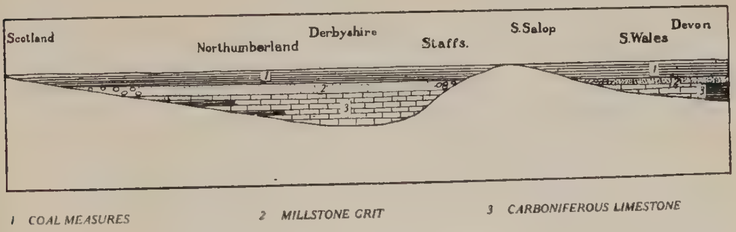

FIG. 8.—DIAGRAMMATIC SECTION ILLUSTRATING THE DEPOSITION OF THE CARBONIFEROUS ROCKS.

During Carboniferous Limestone times there were two main areas of deposition separated by a land ridge (St. George's Land). Later carboniferous sediments encroached upon the ridge, and the Coal Measures were, in places, deposited over it. The carboniferous strata become thinner near the buried ridge, and in the north and in the south the Carboniferous Limestone is, in part, represented by shales and sandstones—material brought down by rivers from the neighbouring lands. The section is purely diagrammatic and is not to scale.

Although, as we have seen, where limestone and ordinary sediments such as mud and sand are accumulating simultaneously, the limestone will be deposited farthest from the shore, this does not necessarily mean that all limestones have been deposited in deep water—indeed the contrary is often the case, for the essential condition is that the water shall be practically free from mechanically derived material, and that may be the case in shallow water near the land if no streams of any size are bringing sediment down to the sea, and if wave-destruction along the coast is negligible.

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* For the meaning of this and other names applied to rocks, see the Table on page 57.

The evidence yielded by dredging indicates that in really deep water calcareous material, such as will ultimately give rise to limestone, does not accumulate at all. This is because calcium carbonate, its principal and in some cases almost its only constituent, although practically insoluble in pure water, dissolves in the presence of carbon dioxide, which occurs in most natural waters (see also page 298). At the surface of the sea, evaporation and changes of temperature may cause the loss of some of the carbon dioxide, with the result that the surface layers of water may be unable to retain all the dissolved calcium carbonate, some of which will be precipitated. Under certain conditions such precipitated calcium carbonate may accumulate on the sea floor giving rise to a limestone of purely chemical origin. This was found to be the case when observations were made some years ago in the delta of the Rhone, but no commercially important limestones appear to have been formed in this way, although certain thin and impersistent calcareous rocks (cornstones) in the Old Red Sandstone formation may have been deposited from solution in inland waters: these will be referred to at a later stage.

Under ordinary circumstances, however, the deepest seawaters are not saturated with calcium carbonate because, owing to the decomposing organic matter that is present on the sea floor, carbon dioxide tends to be more abundant in deep than in shallow water, and, in consequence, the precipitated material is dissolved as it falls; in a similar way, the shells of animals living near the surface tend to dissolve, when, on the death of the creature, they fall to the bottom. The result is that calcareous material does not accumulate on the sea floor where the water is very deep; its maximum deposition, as an open-sea deposit, takes place at a depth of between 1,000 and 1,500 fathoms.

Assuming the formation of a series of sediments such as those described—if the land were to be elevated, the sea would retreat from it, and the zones of sedimentation would move seaward (*Fig.* 9B). As a result, pebbles would be deposited where sand formerly accumulated, sand would be laid down upon mud, and mud upon limestone. If, on the other hand, the land subsided, the seashore would advance upon it and the zones of sedimentation would move landward, so that sand would be deposited upon pebbles, mud upon sand, and limestone upon mud (*Fig.* 9C). This is the reason for the vertical variations seen in sedimentary series, and according as the conditions affecting the nature of the deposit changed slowly or suddenly, the vertical passage of one rock into another will be gradual or sharply defined.

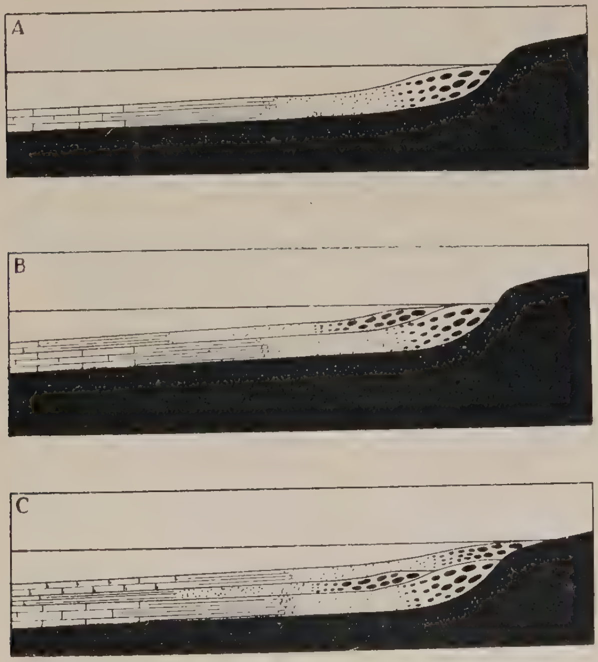

FIG. 9.—DIAGRAM ILLUSTRATING THE ACCUMULATION OF SEDIMENTARY ROCKS, AND THE EFFECT OF ELEVATION AND SUBSIDENCE IN CAUSING VERTICAL CHANGES IN THE SEDIMENTS.

In *A*, the material derived from a land mass on the right has been deposited on the floor of the adjacent sea—pebbles near the shore, followed by sand, mud, and limestone; *B* and *C* represent the conditions after an elevation of the land (*B*) followed by subsidence (*C*).

For example, in parts of the south of England, the Chalk, when traced downwards towards its base, becomes at first slightly and then markedly sandy, before it passes down into the sandstones of the Upper Greensand. Similarly, the Carboniferous Limestone (which, except in the north, is typically a massive limestone) often passes downward into the series of thin beds of impure limestone alternating with shale, that constitutes the real base of the formation; it also passes upward into the sandstones, conglomerates, and shales of the so-called Millstone Grit.

It should be noted that sediments also accumulate in lake basins and in estuaries, thus giving rise to rocks generally similar to those that accumulated in the sea, but to be distinguished from them by the fossils they contain. (Certain organisms, like corals, are entirely marine, and in the case of the molluscs such as snails, winkles, and oysters, the marine, estuarine, and freshwater forms are, with few exceptions, distinctive.)

Lakes are, however, in a geological sense, temporary features, for they tend to become filled with sediment brought down by the rivers that discharge into them, giving rise to level and often fertile plains, or they may be drained in consequence of the erosion of the barrier that determined the level of water; moreover, the deposits formed in them are often subsequently removed by atmospheric denudation and stream action, and even if preserved, will be much less extensive than is the case with deposits of marine origin. Freshwater limestones are not abundant in this country; among them may be mentioned the so-called *Purbeck "Marble,"* and certain light coloured limestones in the Isle of Wight, but none of those beds is now regarded as commercially important.

The Purbeck marble is an impure limestone of freshwater origin found in the Isle of Purbeck, near Swanage (*Fig.* 10). It consists of the shells of a freshwater snail (*Viviparus,* formerly called *Paludina*), in a bluish or grey matrix, and it occurs in thin beds, having been deposited on lake-floors or in estuaries. Among the Tertiary strata of the Isle of Wight there are certain rather soft, cream coloured limestones, often crowded with the shells of land and freshwater snails (*Fig.* 11). At one time, a bed of such limestone, some twenty feet in thickness, was quarried for building stone near Ryde.

In the formation of some freshwater limestones, including those of the Isle of Wight, certain aquatic plants have played an important part. The plants, which belong to the stone-wort group, take up lime and incorporate it into their cells, so that when, after the death of the plant, its vegetable matter has decomposed, there still remains a calcareous mud, which, either alone or mixed with shells, produces material that when consolidated becomes limestone. *Chara* is one of the best known of the lime-secreting plants, and its fruits, consisting of little spherical bodies, about the size of pins' heads and frequently beautifully ornamented with spiral ridges, are often to be found as fossils in freshwater limestones; see *Fig.* 157 and Additional Note, p. 453.

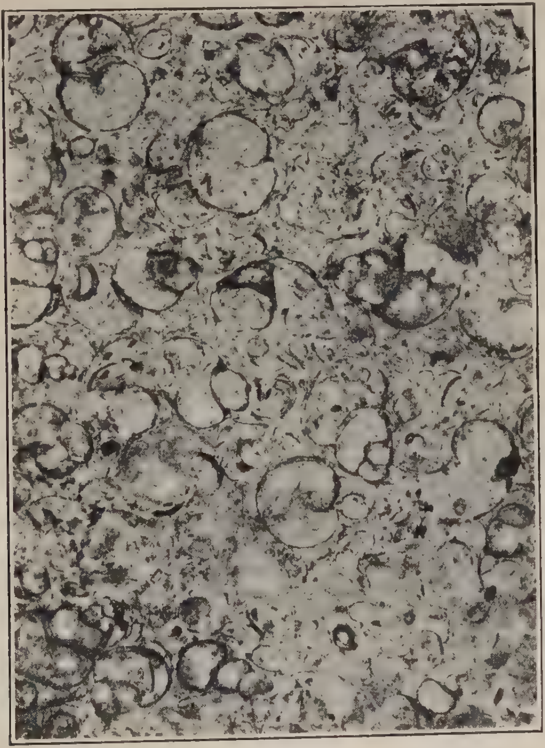

FIG. 10.—A FRESH-WATER LIMESTONE.

"Purbeck Marble"—a limestone consisting largely of the shells of a univalved mollusc, the fresh-water snail, *Viviparus;* about natural size.

The object of the foregoing brief account of the formation of sediments is to demonstrate the relation between limestone and the rocks with which it is likely to be associated. General principles only have been introduced, and some of the statements might, in other circumstances, call for qualification, but those who may desire to have further information should consult a standard text-book on geology [3-6].

The conversion of sediments into rocks.—We now have to consider the processes by which soft, incoherent deposits that were laid down on sea- or lake-floors were converted into compact and often hard rocks—the materials from which the hills and valleys of dry land areas have been fashioned.

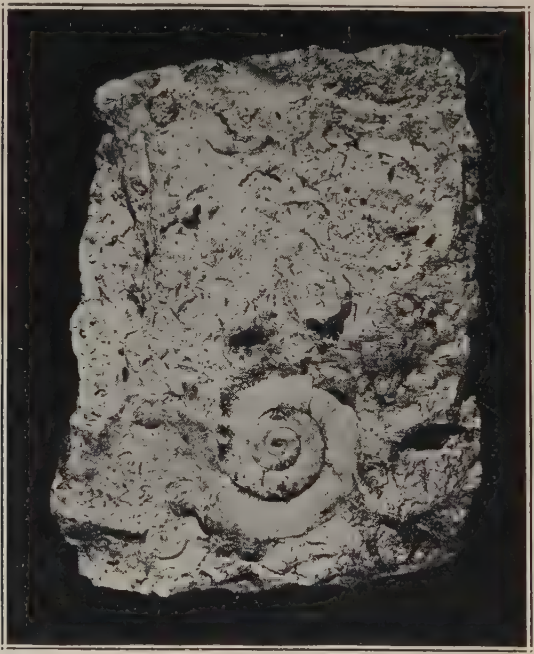

FIG. 11.—A FRESH-WATER LIMESTONE.

Cream coloured limestone containing the shells of fresh-water snails (*Planorbis*), from the Oligocene rocks of the Isle of Wight; about natural size.

The processes of denudation and sedimentation have been in operation since the condition of the earth permitted the formation of oceans and of rain; but from time to time, movements in the earth's crust have caused local changes in the distribution of land and sea. Land areas have sunk beneath the sea, and parts of the sea floor have become dry land; and, as a result, the sediments which had accumulated at the bottom of the sea became the rocks of the newly formed continents, and were, in their turn, subjected to denudation and transport, providing material for the formation of new deposits elsewhere; *Fig.* 12.

During the progress of such movements, strata which were originally deposited as horizontal or nearly horizontal layers of soft materials were rendered compact and hard, and were often thrown into folds (*Figs.* 13, 14 and 42); then, after a period of elevation above sea level during which the crests of the folds were worn away by denudation, they sank, and once more formed the floor of the sea while newer deposits were laid down upon them. There would thus be a considerable interval of time between the formation of the two sets of rocks, and, probably, a considerable difference between the angles which their respective beds make with the horizon; such a relation between two sets of rocks is called an unconformity (*Figs.* 15 and 16).

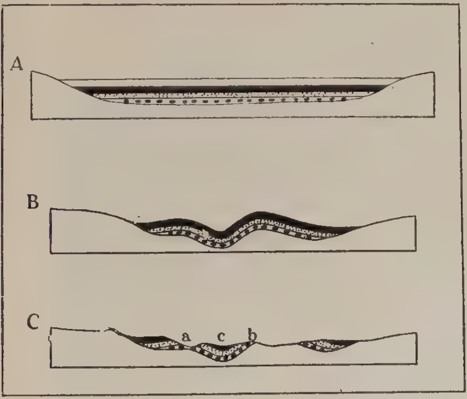

FIG. 12.—DIAGRAM ILLUSTRATING FOLDING AND DENUDATION OF STRATA.

A represents a series of strata deposited in an ocean basin or a lake. As a result of folding (*B*) and denudation (*C*) the sediments laid down during one period become the rocks of a land area in a later period. Owing to the orderly arrangement of the strata, the nature of the rocks underground at one place (*c*) can often be inferred from a study of those appearing at the surface elsewhere (*a* and *b*).

The stresses accompanying movements in the earth's crust often resulted in the strata being locally fractured, and sometimes displaced along the line of fracture, giving rise to "faults" (see *Fig.* 17), that affect not only the continuity of the rocks as they occur beneath the surface or as they may be exposed in cliffs and artificial excavations, but also control and modify the appearance at the surface of any particular stratum or group of strata.

Before being uplifted, the sediments may have been deeply buried beneath other sediments the pressure of which would render them more compact, and, in addition, further pressure would be experienced during periods of crustal movement. In many cases, the sediments were so deeply buried as to have come under the influence of the high temperatures which exist in the deeper layers of the earth's crust, and the effect of the heat has contributed to the induration of the rocks by bringing about changes in the mineralogical arrangement of their constituents. It will, of course, be realised that rocks which have been buried to this extent owe their present position at the surface to the removal by denudation of the strata which had been laid down upon them; *Fig.* 1.

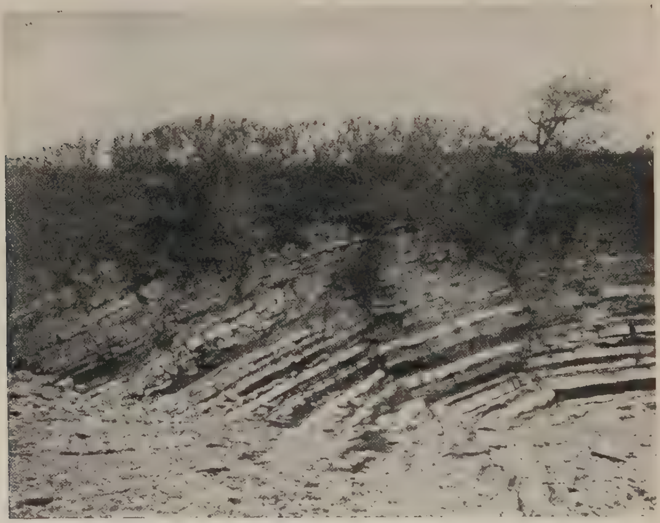

FIG. 13.—LIMESTONES AND SHALES OF THE LOWER LIAS AT BARRY HARBOUR, GLAMORGAN.

In this case, beds similar in age and character to those illustrated in Fig. 2 have been gently folded. (*Photo F.F.M.*)

Once elevated into the condition of a land area, the sediments would tend to dry, and their consolidation would be further advanced by the deposition between the constituent particles of any mineral matter that may have been dissolved in the water with which they were saturated. The process of induration would continue as a result of the percolation through the rock of water that soaked in from the surface—dissolving material in one place and depositing it elsewhere. The result of all these changes is that sands have been compressed and cemented together forming sandstone; muds have become clay, shale, or even slate; whilst accumulations of shells and limy muds have become limestone.

It is obvious that the more remote the period at which the sediment was formed, the more likely it is to have been affected during periods of earth movement, and the longer will all the processes tending to hardening and induration have been operating; and, as a result, it is usually found that the rocks of the older geological formations are harder than those of more recent origin. The Chalk, for instance, is usually soft and friable, while the Bath and Portland limestones, which are older, are harder and more compact: the still older limestones occurring in the Carboniferous and Devonian formations are, for the most part, massive, non-porous, and in many cases sufficiently hard to be polished. Limestones that have been metamorphosed and converted into

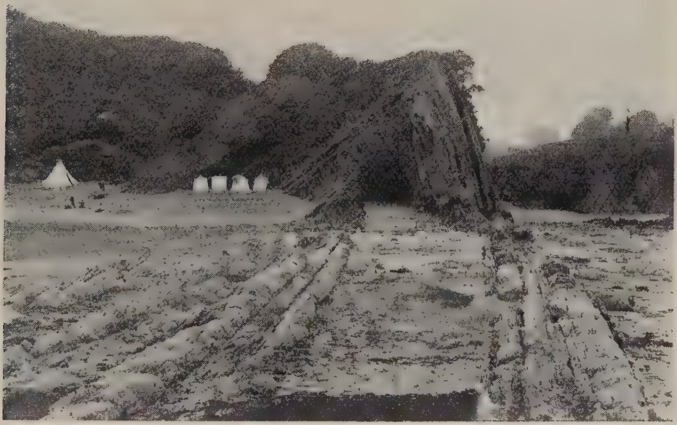

FIG. 14.—FOLDED STRATA AT SAUNDERSFOOT, PEMBROKESHIRE.

Rocks of varying hardness (shales and sandstones of Coal Measure age) have been folded, and while sub-aerial denudation has produced an irregular surface on the land, the sea has reduced the edges of all the strata to the same general level; reproduced by permission of the Director of the Geological Survey.

granular crystalline marbles are still more compact, as the following figures (relating to progressively older sedimentary rocks and a metamorphic rock) indicate:—The weight of a cubic foot of Chalk is 100.7 lbs., of Portland Stone 136.2 lbs., of Doulting Stone (Inferior Oolite) 129.1 lbs., of Hopton Wood Stone (Carboniferous Limestone) 141.4 lbs., and of Carrara Marble 146.2 lbs. The rocks may also be compared by considering the percentage of the total mass represented by the pore spaces between the particles. For Chalk it may be as much as 46 per cent., Portland Stone, 12.8 per cent., Doulting Stone 14.46 per cent., Hopton Wood Stone, 8.36 per cent., and Carrara Marble, 0.78 per cent.

There are, of course, exceptions to this general rule, for, owing to local conditions, some rocks may have been subjected to greater degrees of heat and pressure than rocks of similar age elsewhere. For example, the geologically recent Tertiary limestones of the Isle of Wight are comparatively soft and porous, but similar rocks occurring in the Alpine regions, where the effects of earth-movement are very pronounced, are hard crystalline marbles.

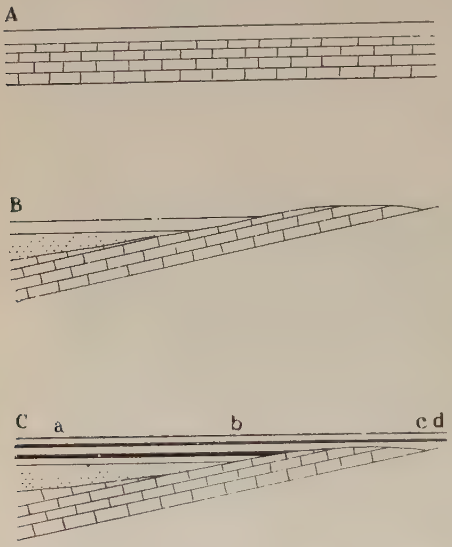

FIG. 15.—Diagram illustrating unconformable strata and "overlap."

In B, the series of deposits represented in A has been elevated (on the right), so that while deposition continued in one part of the area represented, denudation took place in another; continued subsidence may cause newer strata to overspread the whole area (C), with the result that a complete sequence of rocks occurs at (a), while between (b) and (c) some of the strata are missing.

Since the older rocks are usually harder, and hard rocks are more resistant than soft ones to atmospheric weathering and erosion, it follows that, in general, the older rocks tend to give rise to higher ground. In the south of Britain, for example, the general level tends to rise towards the north and west, where, in the mountains of Snowdonia and the Lake District, the rocks are much older than those of the south-eastern counties.

It is not possible here to enter fully into the question of the origin of the movements that have been responsible for changes in the relative level of parts of the earth's surface and for the deformation of its crust. The existence, on land areas, of material that must have accumulated beneath the sea, and the frequency with which rocks exhibit folding, contortion, and faulting, are sufficient indications that such movements have taken place.

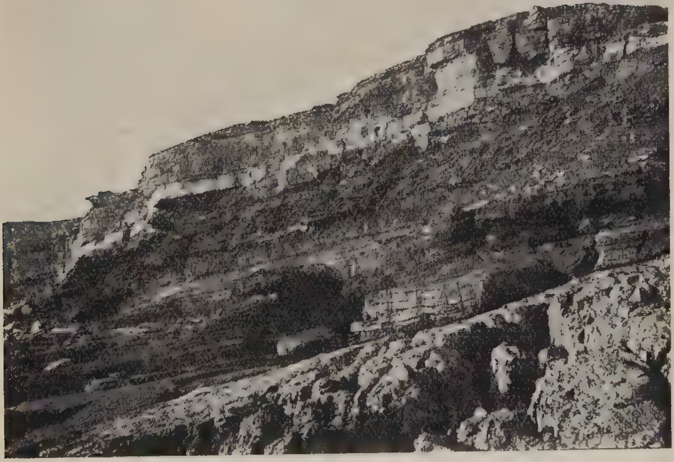

FIG. 16.—AN UNCONFORMITY: CLIFFS AT SULLY ISLAND, GLAMORGAN.

The upper portion of the cliff consists of marls and limestones of Triassic age, resting on an eroded surface of Carboniferous Limestone: the surface of the latter passes obliquely across the photograph from the lower left hand corner. (*Photo F.F.M.*)

It used to be supposed that rocks had been squeezed as a result of the cooling and consequent contraction of the earth, but the shortening of any particular section of its surface from that cause would not be adequate to account for all the rock-crumpling that has taken place: for example, the folds in the

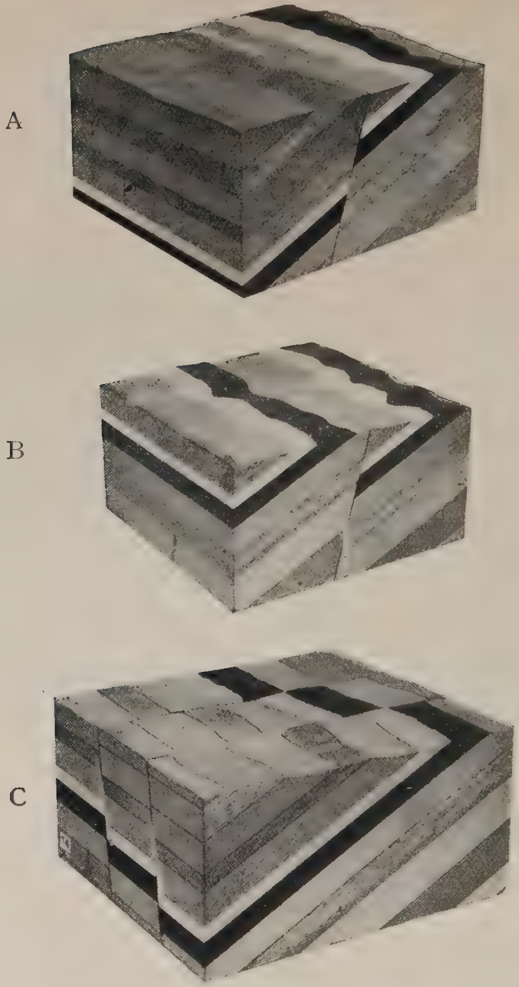

FIG. 17.—FAULTS AND THEIR EFFECT UPON STRATA.

The models illustrate some of the effects of faults or dislocations upon inclined strata. In (A) the fault has resulted in beds being carried to a level lower than that which they would normally occupy: in (B) the strata on the left-hand side of the fault have been thrust upward and certain outcrops have been duplicated, while in (C) the faulting has not only influenced the relative depth of the strata beneath the surface, but has rendered their outcrops discontinuous.

Alpine and Jura systems of mountains represent compression to the extent of seventy-four miles. Recent work by many investigators has shown that the average density of the rocks of continental masses is less than that of the material existing beneath the ocean floors; that is to say, the continents may be regarded as masses of relatively light rock resting on a substratum of heavier material, which, owing to its depth beneath the surface, behaves like a viscous fluid. If the thickness or the weight of one of the continental masses should change, it must of necessity either rise or sink according to the nature of the change; if it sinks, the sea will encroach upon its margin, and if it rises, areas formerly covered by the sea will become dry land.

The changes that would lead to alterations of level are varied: for example, prolonged denudation may reduce the thickness of a continental mass and cause it to rise, or the outpouring of vast quantities of lava during volcanic eruptions may increase its weight and cause it to sink. During the progress of such adjustments the material at the margins of the moving blocks would naturally be subjected to compression, but a further cause of compression is indicated in the suggestion, made by F. B. Taylor (from observations in the United States) and further developed by Alfred Wegener of Graz in Austria, that the continental masses are able to drift about somewhat after the fashion of icebergs floating in the sea. While there are serious difficulties connected with the theory of "continental drift" it certainly explains many phenomena more satisfactorily than any other theory, and amply justifies the great amount of attention that it is attracting. For example, the intense compression of the strata in the Mediterranean region during Tertiary times—compression that built up the great mass from which the Alpine mountains have been carved by denudation—may well be attributed to the squeezing of strata between the great European and African masses (as between the jaws of a vice) as the southern mass drifted against that to the north: the subsequent retreat gave rise to the depression now occupied by the Mediterranean Sea.

Further discussion of this intensely interesting and complicated problem is outside the scope of this book, but the brief outline given will be sufficient to indicate the trend of modern thought and investigation: for more detailed information the works of the protagonists themselves should be consulted [7-13], and they are, fortunately, for the most part books that can be appreciated by those with no special training in the subject.

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CHAPTER II.

THE PROPERTIES AND VARIETIES OF LIMESTONE.

> "The calcareous mountains in Derbyshire . . . contain throughout their whole extent fossil remains of marine animals, but more abundantly in some parts than in others. Particular species occupy almost exclusively distinct beds, and in some situations the whole mass appears a compact congeries of mineralised organic remains."
>
> R. BAKEWELL, in "*Introduction to Geology*," 1828.

We are now in a position to discuss the properties and characteristics of limestone, and to appreciate the relationship which exists between its many varieties.

From what has been said concerning the origin of limestones in general, it is to be expected that the rock will display much variation in composition, appearance, colour, texture, porosity, and hardness, while the beds in which it occurs will vary in thickness, in the development of structural features such as bedding and jointing, and in distribution.

The properties of limestones.—Two properties similar in most varieties are the degree of hardness and the solubility in acid. All limestones can be scratched easily with a knife, and all effervesce briskly with cold dilute acid, such as hydrochloric acid. The specific gravity varies according to the nature and amount of the impurities present: in a fairly pure compact limestone of Carboniferous age it is about 2.72.*

The essential constituent of limestone is *calcium carbonate* (often referred to as carbonate of lime), which, if the rock is pure, will be present to the extent of 98 or 99 per cent.; but various other substances may also be present, and even if the rock contains only 50 per cent. of calcium carbonate it would still, in many cases, be classed as limestone. The principal impurities that may occur are magnesium carbonate, silica (usually in the form of sand), clayey material, salts of iron, and organic matter. There is, naturally, no sharp division between rocks containing sufficient calcium carbonate to be called limestones, and those to which other names should be applied.

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* The specific gravity of a body is its weight compared with the weight of an equal volume of water; or, expressed in another way, it is the number of times the weight of a certain volume of a substance contains the weight of an equal volume of water.

If the proportion of sand or clay is small, the rock may be designated "sandy limestone" or "argillaceous limestone" respectively; but when those substances predominate, the terms calcareous sandstone, calcareous clay (marl), or calcareous shale are applied. If the proportion of magnesium carbonate is considerable, the rock becomes a dolomitic limestone, and, if it is in the neighbourhood of 40 per cent., a dolomite.

The colour varies according to the composition. Pure limestones are nearly white or cream coloured; much carbonaceous matter causes the rock to be grey or even black, although grey tints are also due to the presence of iron sulphide in a finely divided state, and are seen in argillaceous (or clayey) limestones. On account of the organic matter they contain, many dark limestones give off an unpleasant fetid odour when struck or broken. Iron compounds give rise to red, yellow, or brown tints; and the brilliant colours often seen in metamorphosed limestones (marbles) are due to the formation of various minerals from the impurities contained in the original rock.

When weathered, pure limestones tend to develop a thin light-coloured crust, but impure varieties, especially those containing iron, weather yellowish or brown, and if there is much clay or sand, the weathered crust is relatively thick. The latter is due to the fact that the weathering of limestone involves the removal in solution of calcium carbonate, and if much insoluble material is present, it tends to remain behind, forming a superficial layer usually different in colour from the unweathered rock, and sandy or earthy to the touch.

The texture, porosity, and toughness of a limestone will depend largely upon the nature of the sediment from the consolidation of which it has been formed, and these properties can best be referred to at a later stage.

Although, as would be expected from their mode of origin, the different varieties of limestone graduate one into another, it is convenient to classify them according to their mode of origin or fossil contents, and the more important kinds are enumerated below.

Limestones consisting principally of calcareous material secreted by organisms—fossiliferous limestones.—The majority of limestones owe their origin to the accumulation of shells (*Fig.* 18) or other supporting-structures of animals or of plants; sometimes the material was of a mixed character, but frequently the deposit comprised one kind of skeletal substance only, making it possible to distinguish varieties such as shell-limestone, and coral-limestone.

Shelly limestones. — These consist largely of the shells of molluscs* or of brachiopods, in some cases much broken, and in others almost or quite whole (see *Figs.* 10 and 11). The spaces between the shells may have been filled with broken shelly material or with fine calcareous mud, and, according to the extent to which the cementing process proceeded, the resultant rock may be massive or friable, compact or cavernous, hard or soft.

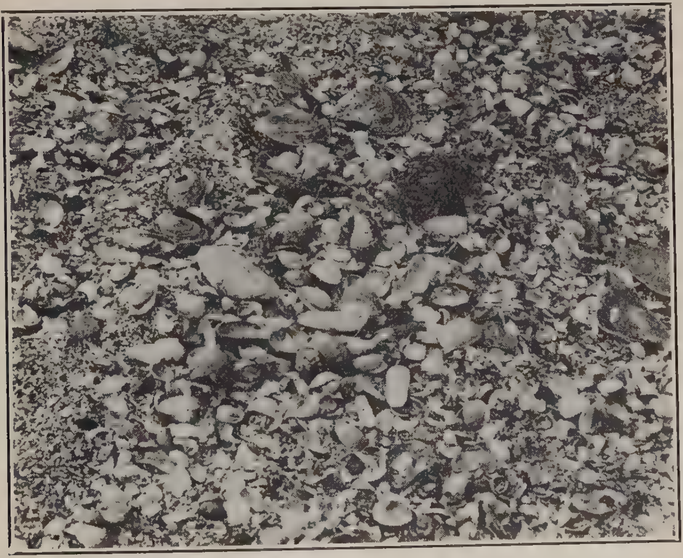

FIG. 18.—SHELLS ON A MODERN BEACH;
such material, under certain conditions, may give rise to limestone. (*Photo T. W. Reader.*)

Many shell-limestones contain one kind of fossil only; for example, certain limestones in the Lias are crowded with oysters (*Fig.* 19), others in the Carboniferous Limestone series with brachiopods (*Fig.* 69), while ammonites and various kinds of univalved shells (gastropods) may also have given rise to shelly limestones.

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* For notes upon the classification of the members of the animal kingdom see Appendix I. (page 430).

In well-consolidated shelly limestones the fossils are often no easy to see on freshly broken surfaces, but, owing to difference between the resistance to weathering of the shells and of th matrix, the existence of the former is at once apparent o weathered surfaces. On such surfaces the fossils may stand ou in relief, but sometimes, as in the case of certain beds of Portland stone, the shells have been entirely dissolved away, leaving a rock crowded with hollow moulds (*Fig.* 20).

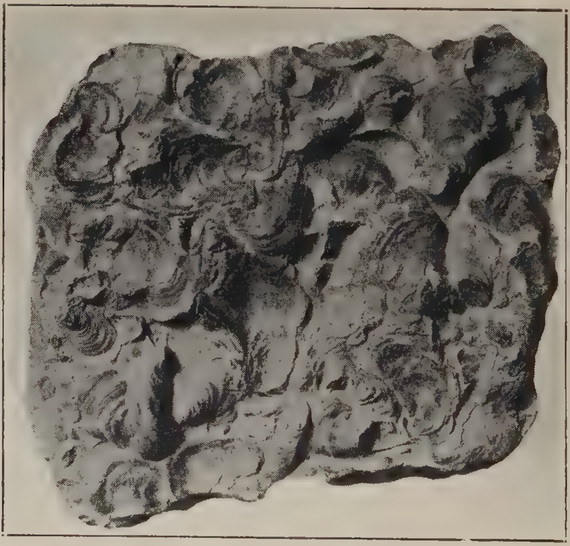

FIG. 19.—A SHELLY LIMESTONE.

The rock, from the Lower Lias of Barry, Glamorgan, is crowded with the shells of a kind of oyster, *Ostrea liassica,* Strickland; half natural size.

In some limestones the shells have been more or less completely obliterated as a result of subsequent changes, such as recrystallisation, due, (*a*) to the action of percolating water, or of heat and pressure that may have converted the rock into marble, or (*b*) to chemical changes resulting in the conversion of the rock into dolomite.

Coral limestones.—The action of corals in building up reefs of calcareous material in certain of the warmer seas is well known, and among the rocks of the earth's crust there are many limestones built up of fragments of coral skeletons or representing ancient coral reefs; *Fig.* 21.

Although coral skeletons are the most conspicuous features of many limestones, other organisms such as marine algæ, mollusca, and foraminifera, have provided a good deal of the material that occupies the spaces in and between the coral skeletons, for not only do such creatures live about coral reefs, but the action of the waves results in the breaking up of some of the coral material and the shells, thus producing calcareous sand and mud that may come to rest among the coral colonies or may be carried by the currents out to sea. After a storm the water near a coral reef is often quite milky, and it has been estimated that coral sand and mud covers nearly three and a quarter million square miles of the sea floor. In many limestones the coral skeletons are very well preserved, and show, on polished surfaces, all the details of their structure. Some rocks of this type which are capable of being polished are used for ornamental purposes, as for example, the *Torquay Marble* of Devonshire, *Fig.* 21, and the *Frosterley Marble* of Durham, *Figs.* 78 and 214.

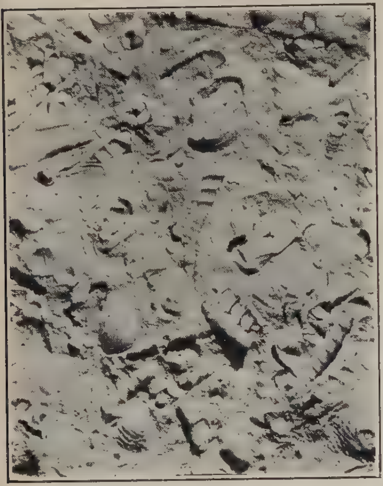

FIG. 20.—ROACH OR ROCHE, a shelly limestone associated with the Portland oolite, in which the fossils are now represented by casts and moulds, the original shells having been dissolved away by percolating water, giving rise to a cavernous rock; about one-eighth natural size.

Crinoidal limestones. — Crinoids are animals related to sea-urchins and starfishes, and they were formerly much more abundant than at the present time. A crinoid may be regarded as a kind of stalked starfish, with a stem, a "cup" enclosing the body, and numerous many-jointed arms (*Fig.* 22), and they have been important as limestone formers because their massive skeletons consist almost entirely of calcium carbonate, and because they were sometimes so abundant that the fragments of those skeletons have built up thick and widespread deposits; *Fig.* 23.

Crinoidal limestones are especially well developed in the Carboniferous Limestone, but they occur also in many other deposits. As is the case with the corals, the crinoid fragments are often well preserved, and give the rock a quaint, if not beautiful, appearance when polished. Examples of ornamental crinoidal limestones in this country are the *Bird's Eye Marble* of Derbyshire, and the *Halkyn Marble* of North Wales. The former is a greyish rock in which there are eye-like fragments of crinoid stems, and the latter is a dark rock occurring as thin beds in the Carboniferous Limestone near Halkyn, in Flintshire. The *petit granit* (*Fig.* 79) of Belgium is a limestone of similar character.

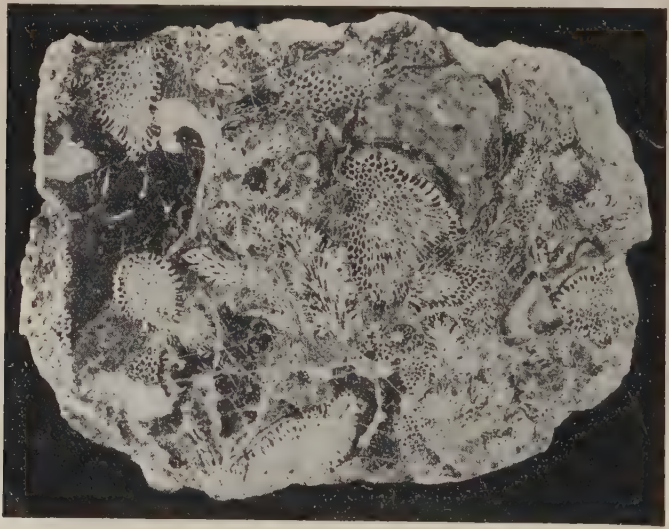

FIG. 21.—A CORAL LIMESTONE.

Limestone consisting largely of the skeletons of corals and coral-like animals, from the Devonian rocks of South Devonshire; about half natural size.

Other fossiliferous limestones. In addition to those already mentioned, there are other animal groups the members of which secrete calcareous supporting-structures that can give rise to limestones; among these are sponges, the small colonial animals known as bryozoa, and the foraminifera; *Fig.* 142. The latter are lowly single-celled animals that construct a shell, consisting in most cases of calcium carbonate. Deposits of foraminiferal shells are now accumulating on parts of the ocean floor; for example, the "*Globigerina* ooze," so called from the abundance of the shells of *Globigerina*, is estimated to cover nearly 48 million square miles of the sea floor, especially in the Atlantic and southern oceans, and the material contains on an average nearly 65 per cent. of calcium carbonate [1].

Similar shells are more or less abundant in many marine limestones, while some important rocks have been produced almost entirely as a result of their accumulation. An example of such a rock is the *Nummulite-limestone* of Tertiary age, which occurs in North Africa and Central Asia, and blocks of which were used in the construction of the Pyramids; *Fig.* 148. In *Nummulites* the shell was round and lens-shaped (*Fig.* 147), and in some species it ranged up to an inch in diameter—an exceptional size for the foraminifera, most of which are exceedingly small.

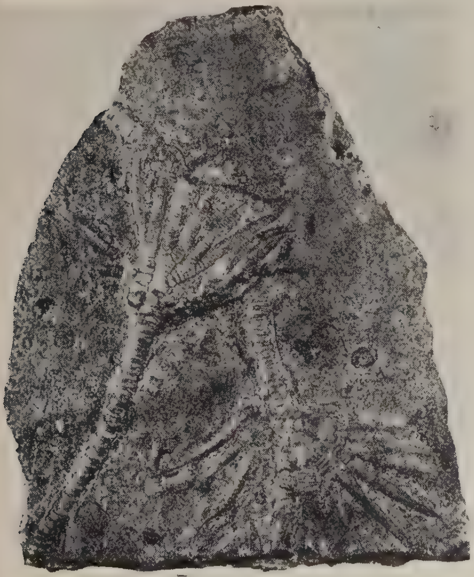

FIG. 22.—FOSSIL CRINOIDS.

Woodocrinus macrodactylus, de Koninck, from the Carboniferous Limestone of Yorkshire; about half natural diameter.

Another rock in the formation of which foraminifera played an important part is the chalk.

Chalk. — This kind of limestone occurs in the upper part of the Cretaceous formation of north-western Europe. It is typically a fine-grained light coloured (often white) rock, dull and earthy, soft and friable, but it varies both in colour and hardness. It consists largely of the shells of *Globigerina* (*Fig.* 142), a member of the foraminifera, together with minute fragments of the shells of molluscs, and of the skeletons of corals and sponges, and contains very little sandy or muddy sediment. In some respects it resembles the foraminiferal ooze of the Atlantic Ocean, but it is not likely to have been deposited in water as deep as that in which the modern oozes are accumulating; see also page 258.

Limestones due to plant growth. — Certain marine calcareous algæ (for example, *Lithothamnion*, a kind of seaweed with a framework of calcite) are limestone formers; *Fig.* 24. Limestones of this character are accumulating in the Bay of Naples, and algæ contribute largely to the deposition of calcareous matter in coral reefs.

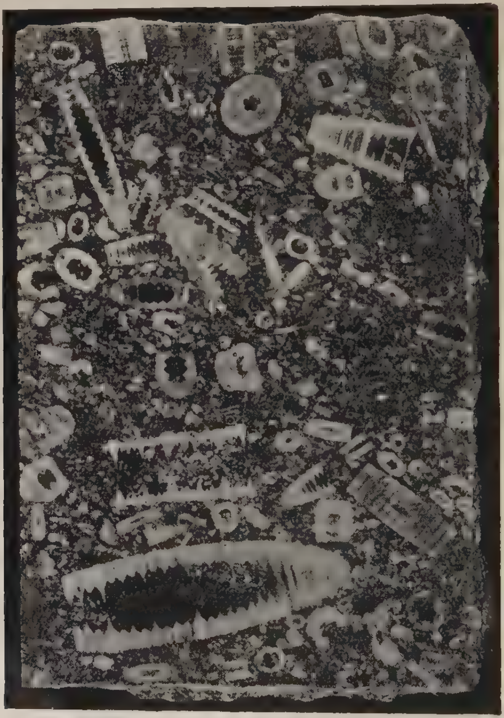

FIG. 23.—A CRINOIDAL LIMESTONE.

Limestone consisting of large fragments of the stems of crinoids in a matrix of smaller fragments of the same material; from the Carboniferous Limestone of Derbyshire; about two-thirds natural size.

Sir Douglas Mawson has described the formation of limestone, under the influence of plant growth, along the coast of South-eastern Australia [2]. The coastal region is low-lying and flat, and the rocks are mainly limestones of Tertiary age, so that the water has every opportunity of becoming highly charged with calcium carbonate, the re-deposition of which is giving rise to new limestones of various kinds. In one place the coast is fringed with permanent lakes, more or less salt, in one of which *Lithothamnion* and other algæ are building a reef of limestone, comparable on a small scale with a coral reef. In another place, small salt lakelets that dry up during the summer months are found to be floored with calcium carbonate in a fine powdery condition, deposited partly as a result of the evaporation of the water and partly by the action of minute blue-green algæ.

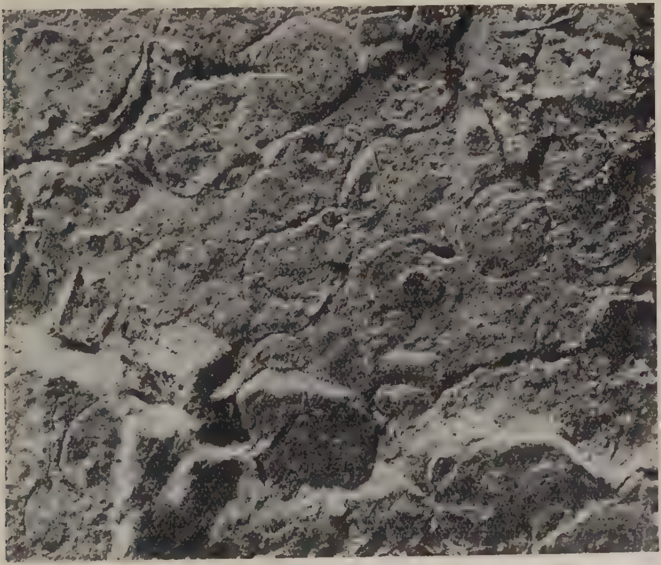

FIG. 24.—LIMESTONE WITH THE REMAINS OF CALCAREOUS ALGÆ.

Photograph, about two-thirds natural size, of a weathered surface of Carboniferous Limestone from Ystradfellte, Brecknockshire; the rock consists of rounded masses, sometimes enclosing corals or fragments of limestone, built up by the activities of calcareous algæ on the floor of the Carboniferous Limestone Sea. The beds in which the algal structure is developed are about 9 inches thick, and the associated limestones are strongly oolitic.

The work of freshwater algæ in contributing to limestone formation has recently been studied in a lake (Green Lake) in the state of New York, where it was found that the algæ are giving rise not only to fringing reefs of limestone, but also to thick incrustations on the trunks and branches of trees that have fallen into the water.

> "All these deposits," continues a report by W. H. Bradley [14], "are exceedingly porous or spongy and consist of more or less closely intergrown arborescent masses. . . . Apparently the form of the limy deposit is determined by the growth and habit of the algæ, for if the calcium carbonate in the softer outer layer is dissolved in dilute acetic acid there remains a very dense felt of algæ which retains the original dimensions and intricate form. Close to the surface, the calcium carbonate, in the form of minute granules, partly fills the interstices between the algal filaments and thus makes a very imperfect mold of the plants. . . . The resulting deposit after the algæ have decayed and completely disappeared is exceedingly porous and exhibits the typical spongy structure. . . .
>
> "The spongy structure of these recent algal reefs is practically identical with that found in many of the fossil reefs. . . . However, few fossil deposits are so porous, because some or even all the interstices have subsequently been filled with calcite or silica These secondary fillings are, nevertheless, clearly distinguishable from the original deposit."

The surface of the deposit has a cauliflower-like appearance, and is greyish green owing to the dense felt of algæ, whose tips are only thinly incrusted with lime. The lower part, which is buried in a soft limy mud, is yellowish grey, dense, and without living algæ. These deposits are of special interest on account of the light they throw upon the origin of similar limestones in the past; see Additional Note, page 445.

Destruction of limestone by organisms.—Certain molluscs, for example, *Saxicava* and *Pholas* (the piddock) bore holes large enough to accommodate themselves in limestone and some other soft rocks, and where many such holes are close together the surface layers of the stone are rendered weak and liable to destruction by wave action, while, where rain water or sea water can accumulate in the holes, the solution of the rock is promoted; *Fig.* 61. In the case of coral reefs, also, the borings made by molluscs and worms, and even by some kinds of echinoderms, facilitate the removal by the breakers of large masses of coral. Even on land, limestones are not immune from this form of attack, for here and there the rock is found to be pitted with holes made by certain kinds of snails, and, naturally, the cavernous surface so produced is favourable to the action of the atmospheric agents of destruction.

In the case of *Pholas* and allied mollusca the boring seems to be achieved by mechanical means. The creatures have been observed making their holes in Chalk, and it was found that they turn from side to side, ceasing work as soon as the hole is deep enough to shelter them. The shell is very hard and rough, and the powdered chalk is ejected at intervals through one of the "syphons" (tubular bodies by means of which water enters and emerges from the cavity in which the gills and mouth are situated), and the space between the shell and the wall of the burrow is filled with the mud produced by the boring process [22]. The piddock never leaves its burrow, but enlarges it from time to time as necessity demands.

There are also sponges, such as that known as *Cliona*, that bore into limestones—probably by the aid of an acid secretion they are able to produce—and the surface of a stone or a pebble that has been attacked is completely riddled with fine tubular holes. Such sponges are serious pests in oyster-beds, for they bore into shells as well. The destruction of limestone by plants and bacteria will be discussed elsewhere.

Limestones, the deposition of which was due largely to chemical and mechanical action. — Reference has already been made to the solubility of calcium carbonate in water containing dissolved carbon dioxide; and water percolating underground, especially when passing through limestone, readily takes calcareous matter into solution. The degree of solubility increases with pressure, and since the pressure naturally tends to increase with depth beneath the surface, underground waters are often found to have dissolved more calcium carbonate than they can hold in solution under normal atmospheric pressures. In consequence, when such waters reach the surface, the reduction of pressure and the tendency to evaporation result in the deposition of some of the calcium carbonate, as travertine, tufa, stalagmite, or stalactite, according to the local conditions. The deposition is, as we have seen, sometimes assisted by the action of algæ and other aquatic plants. The most important travertine deposits are those associated with hot springs occurring in regions of declining volcanic activity; the rock is also known as *calc-sinter.*

Travertine and Tufa. — The names travertine and tufa are often used as though they were synonymous; but if a distinction is made, the soft porous varieties may be called tufa and the harder, more compact forms, travertine. Subsequent percolation of water through the spongy varieties may result in the deposition of calcareous matter within the pores, giving rise to a hard and compact mass. Tufa is usually white or cream-coloured, but the presence of impurities may give rise to shades of brown, red, or even green.

There are important travertine and tufa deposits near Rome, Naples, and Florence, and the material was used in the construction of many buildings—both ancient and modern—in Italy; occurrences in this country will be referred to at a later stage; see page 302.

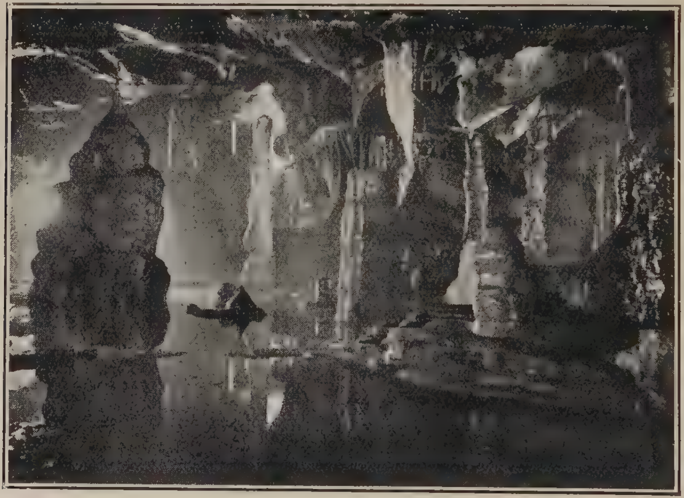

FIG. 25.—STALACTITES AND STALAGMITES IN A LIMESTONE CAVERN.

Cox's Cave, Cheddar. (*Photo Frith and Co.*)

Stalactites and Stalagmite.—Instead of flowing from a spring, water highly charged with calcium carbonate may drip from the roof of a cavern, and, on evaporation, build up, layer by layer, the forms of limestone known as stalactites (cylindrical masses hanging from the roof of a cave) and stalagmite (the hummocky masses lining the walls or floors of a cave); see also page 450 and *Fig.* 25.

Stalactitic carbonate of lime is rarely of commercial importance, although certain coloured and banded varieties, which are sometimes described as travertine, have been used as ornamental stones. These are known by such names as *Oriental Marble,* *Onyx Marble,* and *Mexican Onyx,* and they exhibit tints of green, red, and brown.

Oolitic limestones.—Oolite is composed principally of small, nearly spherical bodies, and in texture it resembles the " hard roe " of fishes; *Fig.* 95. The individual spheres are usually about as large as the heads of pins, but occasionally they are as large as peas, in which case the rock is called " pisolite "; *Figs.* 119 and 121. The grains consist of layers of calcium carbonate arranged concentrically, often about a minute nucleus of sand or shale, and since each layer consists largely of minute prisms or fibres of crystalline calcite, the grains often exhibit a radiating structure also: these structures can be best examined on polished surfaces, or in thin sections; *Fig.* 26.

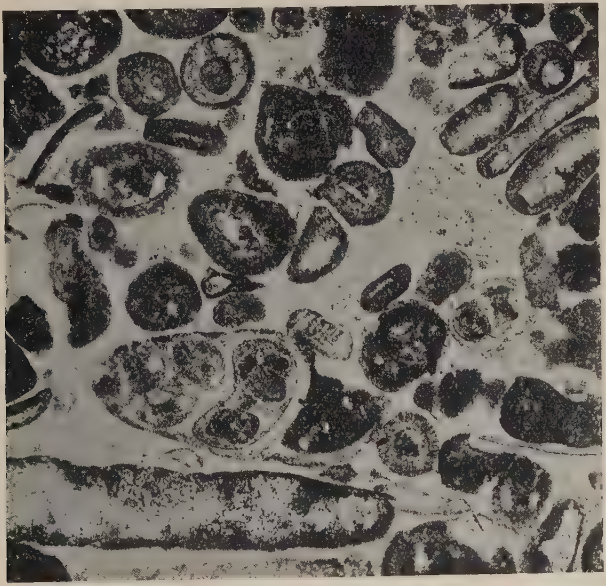

FIG. 26.—AN OOLITIC LIMESTONE.

Photo-micrograph of a thin section of an oolitic limestone from the Liassic Rocks of Glamorgan. The rock consists of round and oval oolitic grains, minute shells, and fragments of larger shells, set in a fine grained calcareous matrix; magnified about twelve diameters.

The oolite grains may constitute practically the whole mass of the rock, or they may form only part of it, the remainder being fragments of shells and other organisms, together with, in many cases, an abundance of entire fossil shells.

Oolitic structure occurs in deposits now accumulating, and is found in limestones of all ages, but in this country it is best developed in the Carboniferous Limestone and in some of the Jurassic (Oolitic) deposits, in connection with which the matter will receive further consideration. Recent accumulations of oolitic grains, in addition to those already mentioned, have been recorded on the coral beaches of the Bahama Islands off the coast of Florida, and in association with the mineral springs of Karlsbad (Karlovy Vary) in Bohemia; the last mentioned example is exceptional, for practically all oolitic limestones are of marine, or at least of salt water, origin.

Limestones of mechanical origin.—Some limestones have been formed by the consolidation of sediments consisting largely of the debris of pre-existing limestones that were undergoing denudation. The original sediment may have varied from fine grained calcareous mud to limestone pebbles, and the resultant limestones also vary in texture from compact fine-grained rocks to limestone-conglomerate. Conglomeratic limestones of this type are seen in the Sutton Stone (a local type of the Lower Lias) in the neighbourhood of Sutton and Southerndown in Glamorgan; see *Fig.* 108; and the thinly bedded limestones, which, alternating with shales, often make up a large part of the normal Lower Lias are primarily fine-grained rocks of detrital origin, although their present characters are in some measure due to concretionary action; see page 193. Such limestones are, as would be expected from their mode of origin, often very impure, and contain much clay or ferruginous matter.

The Carboniferous Limestone, also, includes, in various places, beds of very fine-grained compact-looking limestone, shown by E. E. L. Dixon [3] to have accumulated as fine calcareous mud in shallow water, probably in lagoons. Some of these rocks, on account of their compact appearance, flat fracture, and white or light grey china-like weathered surface, have received the name "china-stone," or "china-stone limestone."

Calcareous deposits due to wind action.—There are numerous examples of clayey and sandy rocks formed by wind action, especially near the sea coast (*e.g.*, sand dunes), in dry regions (*e.g.*, the *loess* of China and elsewhere*), and in deserts, and although in view of the usual mode of deposition of calcareous material, limestones of æolian (wind) origin would not be expected to occur in abundance, if at all, recently formed accumulations of that nature are widely distributed and of considerable interest in the light they throw upon the formation of limestone in the past; and although to do so involves reference to matters that are discussed more fully in later chapters, it will be convenient to mention them here.

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* The loess is an unstratified clay-like deposit that covers large areas in China, and is present also in the valley of the Rhine and on the plains of Poland and Russia: similar material occurring in North America is there

Dunes of calcareous (mostly oolitic) grains occur in a number of places on the shores of the Peninsula of Sinai, especially near the northern end of the Gulf of Suez. The material, deposited in the shallow coastal waters, is thrown up by the waves and spread upon the beach, and is then carried landwards by the wind, giving rise to long dunes parallel to the shore: in some cases it is blown inland for more than two miles.

Calcareous deposits, sometimes friable and sometimes cemented into a hard rock, consisting largely of the shells of foraminifera, are found in various places along the northern shores of the Arabian Sea; and in the coastal region near the mouth of the Indus in Northern India there are calcareous rocks of wind origin that are described as occurring in patches on the hill-side like remnants of a snow drift [17]. This *Junagarh limestone,* so named from the locality in which it occurs, consists of fragments of the calcareous hard parts of shallow-water organisms cemented together by calcium carbonate, and is in places as much as 200 feet thick; it undoubtedly represents material blown from the sea-shore, but it is now 30 miles inland, and the deposit is believed to have been formed at a time when the region stood at a lower level than at present, and when the sea covered what is now dry land [18].

In the Bermudas there are dunes of coral fragments, shell fragments, and foraminiferal shells, and on the Florida coast similar accumulations, more or less indurated by the deposition of calcium carbonate between the particles, constitute the shell-rock known locally as *coquina;* they have also been recorded from other places, such as the Canary Islands and St. Helena.

Most of the foregoing references relate to tropical or sub-tropical regions, and in temperate regions where there are no

known as *adobe*. The deposit appears, in most cases, to represent fine dust blown into enclosed basins over a very long period, and deposited among the growing vegetation. The origin of the dust is obscure, and indeed, is probably different in different regions, but in some cases it was derived from fine mud that was spread about by streams fed by the melting ice towards the close of the glacial epoch [16].

corals, where lime-secreting marine algæ are not abundant, and where the water, being colder, can dissolve more carbon dioxide (and, therefore, more calcium carbonate), shallow water calcareous deposits capable of giving rise to wind-blown limestones are rare, but occasionally, local conditions favour the extensive accumulation of shells or of limestone debris. At Dog's Bay, Galway, on the west coast of Ireland, for example, the Atlantic drift and local currents bring in vast quantities of the shells of foraminifera and small molluscs, which are scattered upon the beach. Between tides, in warm weather, this material dries, and, blown beyond the reach of the sea, it has given rise to a deposit of very small shells and shelly debris covering an area of approximately a quarter of a square mile [18, 19]. A similar shelly deposit on one of the Western Isles of Scotland is mentioned on page 304.

On the shores of the Baltic Islands of Gotland and Oesel, where Silurian limestones are present in force, there are limestone-sands consisting (to the extent of 90 per cent.) of calcareous material, mostly fragments of the fossils that are so abundant in the rocks that make up the cliffs; of somewhat more remote formation are deposits—now "raised beaches"*—containing an abundance of foraminiferal and other broken shells [20], and noticed in Barnstaple Bay by Sir Joseph Prestwich, who, after contributing much, as an amateur, to the development of geology in this country in the middle part of last century, retired from business in 1872 at the age of 60, and two years later became Professor of Geology in Oxford.

The widespread distribution of æolian calcareous deposits (which are, however, individually of comparatively limited extent) suggests that similar deposits must have been formed during past geological ages, and yet records of their occurrence are comparatively rare. For this, several good reasons were adduced by Dr. J. W. Evans who, some years ago, collected much information relating to this interesting phase of limestone formation [18]. In the first place, like all deposits that accumulate on land, their chances of permanent preservation as a rock-layer in the earth's crust are comparatively small. If the land sinks they will most likely be washed away by the advancing waves, and if the land rises or remains stationary, such incoherent material does not usually survive for long the destructive influences of the weather.

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* Raised beaches are sea-beaches situated at some distance above the present level of high tides, and they imply an uplift of the land since the time of their formation.

Moreover, since most of the recent deposits of that nature occur in regions seldom visited and not thoroughly explored, their characters are insufficiently well known to permit of the recognition of similarly formed deposits in the rocks of the geological sequence. Such deposits may, however, be more common than is supposed, as will appear later in connection with our discussion of the Bath Stone and other oolitic limestones. A. W. Grabau of Columbia University [21] even goes so far as to suggest that some part, at least, of the White Chalk is of æolian origin. He compared its fineness of grain, homogeneity, and lack of stratification, with similar characters observed in the loess.

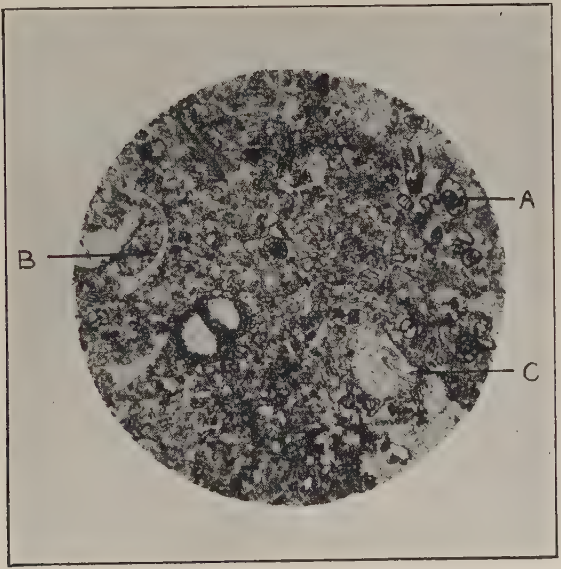

FIG. 27.—SHELLY LIMESTONE; CARBONIFEROUS LIMESTONE, DERBYSHIRE.

Photo-micrograph (magnified 8 diameters) showing small shells (foraminifera, A) and fragments of large shells (brachiopoda, B) in a matrix of calcareous debris, some of which has recrystallised as the mineral calcite (C).

The alteration of limestone. — Limestones are liable to alteration by chemical and physical processes, giving rise to rocks which may be totally different in properties and uses, or which may, for all practical purposes, still be regarded as limestones.

Dolomite and dolomitic limestone, "rottenstone," and oolitic ironstone are examples of chemically altered limestones, while marble is a variety in which changes of a physical character have taken place.

Dolomite and dolomitic limestones.—Any limestone may contain carbonate of magnesium, and if the proportion of that ingredient is more than 20 per cent. the rock is known as dolomitic limestone. True dolomite-rock consists principally of the *mineral* dolomite, which is a double carbonate of calcium and magnesium, and contains those substances in the proportions of 54·35 per cent. and 45.65 per cent. respectively; but the name is also loosely used for rocks that are really only dolomitic, or magnesian, limestones. Dolomites and dolomitic-limestones may have originated, like certain limestones, as chemical deposits

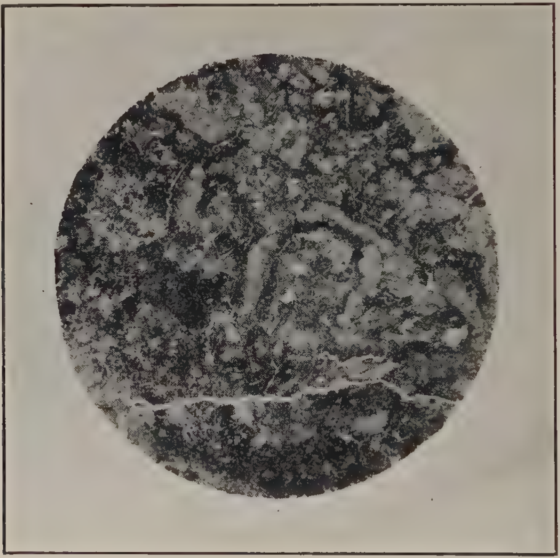

FIG. 28.—DOLOMITIC LIMESTONE, CARBONIFEROUS LIMESTONE, MITCHELDEAN, GLOS.

Photo-micrograph (magnified 8 diameters) showing the rhombic outlines of relatively large crystals of dolomite which have developed in a limestone.

(primary dolomite); or they may result from the alteration of a limestone (secondary dolomite)—the change taking place either during or immediately after the accumulation of the deposit, or long subsequent to its consolidation; see *Figs.* 27 and 29. The change in the former case is called "contemporaneous dolomitisation," and in the latter case "subsequent dolomitisation"; it is usually possible, and often for economic purposes desirable, to determine by which of these processes a dolomitic limestone has been formed [4].

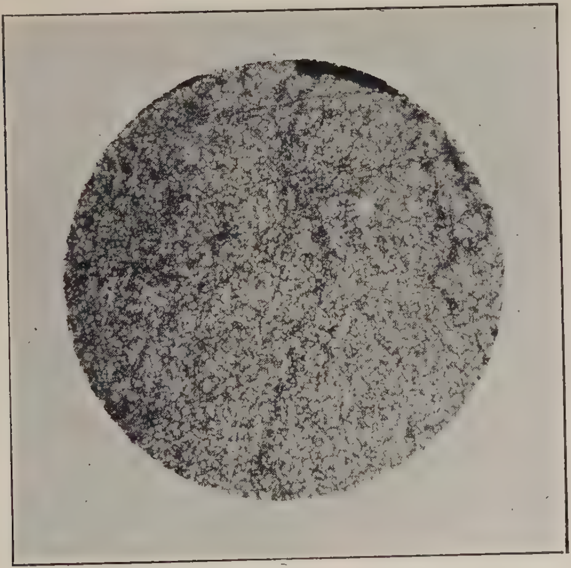

FIG. 29.—DOLOMITE, DEVONIAN, TORQUAY.

Photo-micrograph, magnified about 8 diameters. The rock consists almost entirely of small closely packed crystals of the mineral dolomite.

In this country, dolomite and dolomitic limestones resulting from the alteration of normal limestone occur principally in the Carboniferous Limestone, in connection with which they will be discussed in more detail; while dolomite that has been, or is believed to have been deposited as a result of excessive evaporation of the waters of inland seas or lagoons, is an important feature in the Permian Formation, as for example, near Mansfield.

In the Tyrol, also, there are beds of dolomite of Triassic age associated with gypsum, and undoubtedly due to the evaporation of sea water or of salt water in a desert region; but precipitated dolomites are much less common than those which are altered limestones.

It is not possible here to enter into a detailed discussion concerning the chemistry of the origin of dolomite, and a brief account of the evidence relating to the source of the magnesia must suffice.

Kind of animal or plant	*$CaCO_3$, %*	*$MgCO_3$,%*
Foraminifera	77.02—90.11	1.79—11.22
Calcareous sponges	71.14—84.96	4.61—14.10
Coelentrates, corals, etc.	89.11—99.503	0.22— 6.04
Annelids	89.66—91.55	0.00— 9 72
Echinoderms, starfishes, etc.	80.95—92.11	6.92—14.19
Brachiopods with calcareous shells	88.59—98.61	0.49— 8.63
Brachiopods with phosphatic shells	1.18— 8.35	0.79— 6.68
Molluscs, gastropods, etc.	96.45—99 77	0.05— 2.93
Crustaceans	28.56—82.64	3.65—15.99
Calcareous algæ	73.63—99.21	0.02—25.17

FIG. 30. — TABLE SHOWING PROPORTION OF CALCIUM CARBONATE AND MAGNESIUM CARBONATE IN THE SHELLS AND SKELETONS OF MARINE INVERTEBRATE ANIMALS [12, 13].

Analyses of the shells and other supporting structures of aquatic animals show that they almost invariably contain magnesium carbonate, which is especially abundant in the hard parts of algæ, the foraminifera, the echinoderms, and some crustaceans, and is present in greater proportion in organisms living in the warmer seas (see *Fig.* 30). It therefore follows that the calcareous sediment resulting from the accumulation of shells and other materials that go to the formation of limestone will contain magnesium carbonate, and that substance, as well as calcium carbonate, will tend to pass into solution where the sea-water is not already saturated, with the result that the salts present in oceanic waters include about 12 per cent. of magnesium compounds.

In some way not fully understood, the magnesium carbonate may unite with the calcium carbonate of a newly accumulated calcareous sediment, forming dolomite or dolomitic limestone, and, subsequently, the percolation of magnesium-bearing water through the mass may effect further change.

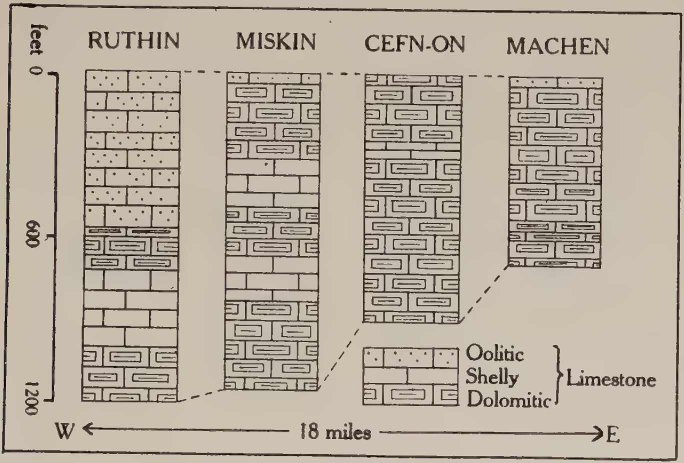

FIG. 31.—THE OCCURRENCE OF DOLOMITE IN THE CARBONIFEROUS LIMESTONE OF SOUTH WALES.

Vertical sections illustrating the dolomitisation of the middle part of the Carboniferous Limestone as it is traced from west to east in Glamorgan and Monmouthshire (after Dixey and Sibly) [3].

In the coral atoll of Funafuti, in the Pacific Ocean, examined in 1896 with a view to determining the conditions under which coral islands and atolls were formed, it was found that while the percentage of magnesium was small near the surface, it tended to increase with depth, until at a depth of 1,000 feet the rock was practically a dolomite. This is an example of a recently formed limestone that, either during or soon after deposition, was dolomitised, and the reports of the Funafuti exploration should be studied by anyone interested in the origin of dolomite [5, 6].

Subsequent dolomitisation, as seen for example in the Carboniferous Limestone, is sometimes very local, and sometimes affects certain beds over wide areas; see *Fig.* 31.

Dolomites and magnesian limestones are similar in general character to ordinary limestones, but, for rocks of similar texture and compactness, they are slightly heavier and harder; they do not, like limestones, effervesce freely with cold dilute acid, but they do so if the acid is hot; this provides a convenient means of distinguishing dolomite from limestone, but it is better when making the test to compare the supposed dolomite with a rock that is known to be a relatively pure limestone. The two kinds of rock are also to be distinguished by their behaviour towards heat, for if heated suddenly in a crucible, powdered dolomite loses its carbon dioxide so rapidly that it may jump right out of the containing vessel, whereas calcite can be strongly heated with safety.

There are also chemical tests by which the presence of magnesia in a limestone may be recognised, but that aspect of the subject is outside the scope of the present work; details of such tests will be found in geochemical treatises [6, 7].

In colour, dolomites are usually pale, and they exhibit shades of cream, brown, red, and grey, although a pure dolomite should be white: the principal impurity present is carbonate of iron, to which the yellow, brown, and red tints are due.

In texture, dolomites and dolomitic limestones range from earthy and compact to crystalline and granular; the latter condition is due to the tendency of the mineral dolomite in a dolomitised limestone to crystallise in minute rhombohedral crystals, the abundance of which sometimes imparts to the rock the appearance and feel of sandstone. The specific gravity of the mineral dolomite (2.83) is slightly above that of calcite (2.72) so that on dolomitisation there is a small decrease in the bulk of the rock, and the shrinkage results in the development of a cavernous or porous texture; the little cavities so produced are frequently lined with rhombohedral dolomite crystals.

The following table illustrates the tendency to an increased porosity in a limestone as it becomes more and more dolomitic. The figures relate to a number of magnesium-bearing limestones and dolomites from various localities in Derbyshire and are selected from a series of more detailed tables given in a paper by Dr. L. M. Parsons [23]. It will be noticed that as the proportion of magnesium carbonate increases, so does the porosity of the rock, although the increase of the latter is not strictly proportional to the increase of the former, because the porosity is not entirely due to the shrinkage consequent upon recrystallisation: the spaces that result from recrystallisation allow water to percolate more freely through the rock and thus further increase its porosity by solution. The porosity cannot be correlated with the specific gravity of the rocks on account of the variations in the amount of iron compounds, silica, and argillaceous material that may be present.

COMPOSITION, POROSITY AND SPECIFIC GRAVITY OF DOLOMITE FROM DERBYSHIRE.

Calcium Carbonate	Magnesium Carbonate	Porosity	Specific Gravity
84.5	10.7	2.2	2.69
83.4	9.9	3.2	2.72
79.4	13.9	3.9	2.65
76.5	20.7	3.4	2.52
64.9	32.6	4.1	2.53
62.3	35.9	5.3	2.49
58.5	38.0	4.3	2.38
56.8	40.5	5.9	2.51
54.2	41.1	5.6	2.67
51.5	40.2	5.9	2.69
49.0	43.7	5.8	2.45

Ferruginous limestone.—Some of the oolitic limestones of the Lias (in Yorkshire and in Lincolnshire) have been so changed in chemical composition as to be suitable for use as ores of iron, although the oolitic structure remains as clearly defined as in the original rock. The chemical processes involved in the change are discussed in a report of the Geological Survey [8], but, briefly, it would appear that the calcium carbonate was first converted into ferrous (iron) carbonate through the action of percolating iron-bearing waters, after which oxidisation has in some cases resulted in the conversion of the ferrous carbonate into the more highly oxidised ferric oxide, in the form of the mineral *limonite*. Oolitic ironstones are usually greenish blue in cases where there has been little oxidation, and brown or reddish brown in other cases. Oolitic ironstones occur in the Liassic rocks at Frodingham in Lincolnshire and Cleveland in Yorkshire, and they are also present in the Corallian beds (Middle Oolite) of Westbury, and in certain of the Cretaceous beds in Lincolnshire and Wiltshire.

Rottenstone.—The complete removal of the calcium carbonate during the weathering of certain siliceous limestones may leave behind what is virtually the siliceous skeleton of the rock. This is known as " rottenstone," and because the silica, which is hard, is in an extremely fine state of subdivision, it has been used for the purposes of an abrasive and as a polishing medium. It usually occurs in thin beds, and, as it is a result of weathering, it is only found near the surface; when followed underground it passes gradually into unaltered limestone.

Decomposed or decalcified limestone in the form of rottenstone occurs, for example, as thin beds in the upper part of the Carboniferous Limestone series about Cribarth and Penwyllt in the South West corner of Brecknockshire [9], and it is also present in the Carboniferous Limestone of the Bakewell district of Derbyshire.

Marble.—Most limestones consist of fragments of crystalline calcite; sometimes, as in the case of certain shelly and crinoidal limestones the rock is *obviously* crystalline, but, as a rule, owing to the small size of the component particles, the crystalline character is less apparent. The term marble, in its scientific sense, is reserved for those limestones which, as a result of the operation of heat and pressure, have undergone recrystallisation, often with the complete obliteration of the original texture. So defined, a marble is a mass of granular crystalline calcite, such as, for example, the statuary marble of Carrara in Northern Italy. As used commercially, however, the term is much more comprehensive, and it is made to include many kinds of limestone, which, owing to peculiarities of texture and colour and the readiness with which they may be polished, can be regarded as " ornamental " stones.

The use of the term in its wider sense may be justified on the grounds that the word is derived from a Greek word meaning a sparkling or shining stone, but it should always be borne in mind that in geological works, marble connotes a metamorphic limestone, and does not include many of the ornamental limestones to be found among the marbles of commerce. For some purposes, the value of a marble, whether correctly so-called or not, depends upon the difference in the appearance of polished and unpolished surfaces: this is more apparent in coloured varieties than in those which are white: a polished surface permits light to enter, to some extent, the crystals of which the rock consists, and thus, not only are the colours of the component materials more apparent, but the surface appears to be darker than one that has not been polished, and which, being somewhat rough or granular, reflects more light: a similar case is seen in the white reflecting surface of snow as compared with the darker shining surface of ice [15].

Many years ago, Sir James Hall, who was one of the pioneers in experimental geology, attempted to convert limestone into marble by the application of heat and pressure [10]. He exposed dry chalk, hermetically sealed in gun-barrels, to the temperature of melting silver (about 1000°C), and found that it did not give off its carbon dioxide as it does when heated under ordinary atmospheric conditions, but was partially melted and crystallised. In the presence of a little water, chalk, similarly treated, was converted into a crystalline mass resembling marble.

A pure limestone, on conversion into marble, becomes a white crystalline mass, not unlike lump-sugar in appearance—this is the case, for example, with the Carrara marble. In the case of an impure limestone, however, the impurities also may enter into new chemical combinations giving rise to coloured materials: it is to these that the beauty of many marbles is due. If organic matter, derived from decaying vegetation, was present in any quantity in the original limestone, the resultant marble will be black, while the bright colours are due usually to the presence of metallic compounds. Iron-bearing minerals give red and brown tints, and copper minerals give green, although green tints are often due to certain silicate-minerals, such as chlorite and talc.

Since, for reasons already discussed, the characters of a limestone deposit are liable to change when traced through the country, the marbles produced by the alteration of limestone include many different varieties, some kinds being extremely local in their distribution.

If the processes that resulted in the change from limestone to marble included violent earth movements, the rock may have been cracked and shattered: in such cases the newly formed minerals tend to develop in the cracks, giving rise to veined marbles; *Fig.* 40; if, on the other hand, the whole rock was smashed into angular fragments, their re-cementation, either by the infiltration of new mineral matter or by pressure, will give rise to brecciated marbles; see *Fig.* 32.

Metamorphic marbles of commercial importance are not common in this country, but some of the older fossiliferous limestones are sufficiently compact and hard to be polished and used for decorative work. Among the former may be mentioned the pink marble of Tiree in the Hebrides, and the green marbles of Connemara and Anglesey; see *Fig.* 40. In some places, an intrusion of igneous rock has converted a limestone in its immediate neighbourhood into crystalline marble, but not usually in sufficient quantity to be of other than scientific interest. This is, for example, the case with the Carboniferous Limestone in the Peak Forest district of Derbyshire, where the rock has been changed by an intrusion of dolerite: for a distance of about five feet from the igneous rock the limestone has been rendered crystalline, hard, and brittle, and the fossils have been obliterated.

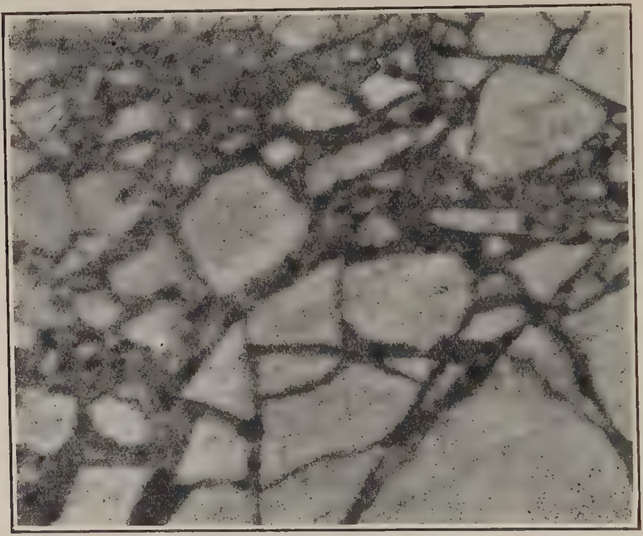

FIG. 32.—A BRECCIATED MARBLE.

The Brèche Rose d'Orient of the Isle of Marmara. The angular fragments are pale pink and the matrix rose-coloured; it will be seen that the original rock has been shattered and the fragments but slightly displaced; photograph natural size.

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CHAPTER III.

THE DISTRIBUTION OF LIMESTONE.

> "The more exact our knowledge of the position and sequence of rock-formations the more certain our economic explorations become; and the more successful our industrial adventures, the greater will be the impetus given to the extension and exactitude of scientific research."
>
> D. PAGE, in "*Economic Geology*," 1874.

The distribution of limestones, geographically, is dependent upon their distribution geologically, for the major surface features of the earth are determined by the nature and arrangement of the rocks of its crust. It is, therefore, desirable to discuss the distribution of limestones in relation to the geological formations among whose rocks they occur, and as that will involve the use of certain terms that are used to distinguish the rocks of one age from those of another, a brief account will be given of the principles upon which rocks are classified according to their relative ages.

The classification of stratified rocks.—Although, considered as a whole, sedimentary rocks occur in layers, the earth's crust does not consist of strata arranged entirely in a regular concentric manner like the coats of an onion. The material was, in the first place, deposited in layers, which were, over limited areas, more or less horizontal, but, as already shown, in many places the beds were squeezed when adjacent masses of the earth's crust moved relatively to one another, and were thrown into folds. Rain and wind—nature's agents of destruction—have worn away the tops of many folds and the denuded material has been used to form new rocks elsewhere; the result is that although sediments to a thickness of many thousands of feet have been formed since the first appearance of water upon the earth, the entire thickness is not preserved in any one locality, although some part of every group into which they have been divided is encountered somewhere or other among the rocks which can be examined in natural exposures or in artificial excavations; and, in addition, we are able to discover, by inference, something of the structure of the earth's crust to a depth of about 20 miles (see *Fig.* 12).

It will be realised, on considering their mode of origin, that sedimentary rocks may, and often do, contain fossils, which are the remains or impressions of animals and plants that lived when the rocks enclosing them were being formed; and since, with the passage of time, the life of the earth as a whole has changed or evolved—new forms appearing as others have become extinct, either rapidly or slowly according to circumstances—the general assemblage of animals and plants at any one period was characteristic of that period, and the individuals were slightly more complex, or more developed in certain directions than those of preceding periods, and were less complex or less developed in certain directions than those of later periods. As a result, the general assemblage of fossils found in any one stratum is characteristic of that stratum wherever it was formed under similar conditions, and serves to distinguish it from other strata, similar in mode of origin and accumulation, and, therefore, similar in lithological characters, but formed at different periods. For example shelly limestones of Siluriar age can be at once distinguished from shelly limestones of Carboniferou age by the fossils the contain.

FIG. 33.—William Smith (1769-1839).

"The Father of English Geology," who prepared the first geological map of England and Wales, and demonstrated the identification of strata by means of the fossils they contain. (Reproduced by permission of the Council of the Geological Society.)

This principle, the application of which laid the foundation o modern geology, was first enunciated by William Smith toward the end of the 18th century. Smith was the son of an Oxfordshire farmer and was himself a civil engineer and land surveyo (*Fig.* 33). As a lad, he showed an interest in stones and fossils and as a man he used to advantage the cpportunities, afforde during the course of his work in land-draining and canal-making to study the peculiarities of the strata exposed at the earth's surface. He noticed that, not only were the various layers of rock arranged in a regular order, one resting upon another, but also that the fossils of each layer were in some way peculiar to it; from this he concluded that fossils provide a means of identifying strata, when, owing to a covering of soil or of rock, parts of their outcrops* are concealed, or when, having been locally washed away, as during the formation of a valley, one part of a formation is completely isolated from another.

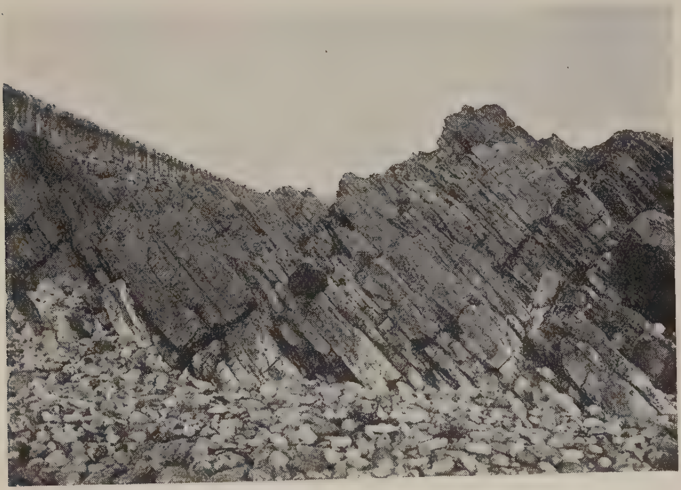

FIG. 34.—"DIP," ILLUSTRATED BY THE CARBONIFEROUS LIMESTONE AT BARRY ISLAND, GLAMORGAN.

There is a beach of limestone pebbles at the foot of a low cliff of Carboniferous Limestone. The photograph should be compared with Figs. 88 and 87, which illustrate similar beaches formed at a remote geological period—the Triassic. (*Photo F.F.M.*)

Making use of these principles, Smith showed that the strata of the earth's crust were arranged in accordance with definite laws, and in 1815 he published a geological map of England and Wales on the scale of five miles to the inch. In addition to being the first true geological map, apart from some small manuscript maps of his own preparing, this great work laid the foundation of modern geological research, and the map became the basis of all later geological maps of this country, and the standard of geological maps for the world [1]. On account of the far reaching effects of his life-work, Smith is often spoken of as the "Father of English Geology."

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* The surface area occupied by any particular stratum is known as its *outcrop*, and the inclination of a stratum to the horizon is its *dip* (Fig. 34), which is estimated in degrees from the horizontal. The extension of an outcrop in a direction at right angles to the dip is its *strike*.

From a study of their fossil contents and their relations one to another, the strata making up that part of the earth's crust which is available for man's investigation have been divided, for convenience of reference and description, into a number of "Formations" and "Systems," to which distinctive names have been given, as indicated in the Table, *Fig.* 35. The names in the first column are those given to the major periods (Eras) of Geological time, and those in the second column relate to their sub-divisions (Periods). The names are applied not only to the divisions of time but also to the rocks formed during them: for example, the strata formed during the Carboniferous Period constitute the Carboniferous System of rocks. In the third column are indicated some of the horizons at which limestones occur in this country.

The names Palæozoic, Mesozoic, and Cainozoic, imply, respectively, "ancient life," "middle life," and "recent life," and are used to designate three of the four major periods of earth-history. The Cainozoic era is also called the Tertiary era, and the Mesozoic, the Secondary. The Palæozoic era corresponds in part to the "Primary" division of the older geologists, but the term Primary is not used in modern geological literature.

During the Palæozoic era the animals and plants were almost entirely of kinds now extinct. The Cainozoic era was characterised by the prevalence of animals and plants closely allied to those now living, whilst the life of the Mesozoic era was intermediate in character between that of the other two. The earliest period was formerly known as Azoic, because it was supposed to have been an age entirely without life, but although no fossils have been found in the oldest rocks of this country, it is quite certain that living things had already come into existence, because the nature and variety of the fossils found in the oldest fossil-bearing strata indicate a very long period of previous development. On this account, the term "Archean" (meaning ancient) is now generally used to designate all the rocks older than the Cambrian. They are also called Pre-Cambrian.

The names given to the smaller sub-divisions of geological time and to the rocks formed during them, refer, in some cases,

FIG. 35.—TABLE OF STRATA, INDICATING THE DISTRIBUTION OF LIMESTONE IN GREAT BRITAIN.

The list is not a complete survey of British Limestones, but indicates only the principal horizons at which they occur. The table does not take into account the thickness of the rocks included in the various Systems enumerated: the period represented by the Pre-Cambrian rocks was, for example, probably as long as all the others put together.

Names given to the divisions of geological time		*Some of the horizons at which limestones occur in the British Isles*
Cainozoic (Tertiary)	TERTIARY & RECENT	Fresh-water limestones of the Isle of Wight, and recent travertines, tufas, and stalagmites.
Mesozoic (Secondary)	CRETACEOUS	Chalk, Totternhoe Stone, Beer Stone, Kentish Rag, Sussex Marble.
	JURASSIC (including LIAS)	Many important oolitic limestones, for example Portland Stone and Bath Stone; and other building stones such as Doulting Stone, Dundry Stone, Forest Marble. Limestones in the Lias are used for building and cement making.
Palæozoic (Primary)	TRIASSIC	Some conglomerates of limestone pebbles occur, and also dolomitic grits, but no normal limestones.
	PERMIAN	The Magnesian Limestones of the eastern side of the Pennine Range; building stones, dolomite, etc.
	CARBONIFEROUS	The lower part of the Carboniferous System consists largely of Limestone—the Carboniferous Limestone—which is used for building, road-stone, lime-burning, chemical works, etc.
	DEVONIAN	Limestones used for building and ornamental purposes occur in the Middle Devonian of Devonshire; calcareous beds occur in the Old Red Sandstone.
	SILURIAN	Limestones occur at various horizons in the Silurian System: they include the Wenlock Limestone, Woolhope Limestone and Aymestry Limestone—used mainly for building, lime burning and metallurgical purposes.
	ORDOVICIAN	Limestones are not important except in the upper part of the Formation: Bala Limestone in North Wales, Coniston Limestone in the Lake District, Shoalshook Limestone in South Wales.
	CAMBRIAN	The Durness Limestones and Dolomites of the north-west of Scotland are, in part, of Cambrian age, but limestones of commercial importance are not abundant in England and Ireland.
Archæan	PRE-CAMBRIAN	Few limestones occur in the Pre-Cambrian rocks of this country; most of them are now crystalline marbles and few are of economic importance.

to the district in which the rocks were first studied or are very well displayed; for example, the Cambrian strata are well developed in Wales, the Ordovician and Silurian in those parts of Wales and the border counties occupied by the ancient tribes of the Ordovices and the Silures respectively, the Devonian in Devonshire, the Permian in the Russian province of Perm, and the Jurassic in the Jura mountain region of France and Switzerland.

Some of the names allude to the character of the rocks; Carboniferous (carbon bearing) and Cretaceous (chalk bearing), refer to the presence of coal in the former, and of chalk in the latter formation.

It is necessary to bear in mind that this is an artificial classification, and that, as is usually the case in Nature, there are no definite dividing lines between the sub-divisions which have been proposed. If the entire thickness of sediment that accumulated in any one area had been preserved, the rocks would there present an unbroken sequence: as it is, where no rocks are missing, the passage from one formation into another is often so gradual that there is considerable difficulty in deciding where the dividing line should be drawn. This is the case, for example, with the Devonian and the Silurian formations, for even after many years of careful research, authorities are not agreed as to whether certain beds should be regarded as representing the top of the Silurian, or the bottom of the Devonian [2, 3].

In other cases where there is a well defined separation, as there is in this country between Pre-Cambrian and Cambrian rocks, and between those of the Cretaceous period and those of the Tertiary era, it is because there is a gap in the sequence, and a considerable thickness of rocks is missing, owing to the fact that the older series was uplifted and in part denuded away before the newer series was laid down.

Geological maps.—A geological map is one which, in addition to showing the physical and topographical features of the district to which it relates, indicates also the nature of the rocks that make up the surface layers of the earth's crust (and which would be actually seen if the covering of soil were removed), the area which each kind occupies (its outcrop), and also the relation which exists between them.

In the preparation of a geological map, all the rocks exposed at the surface, whether by natural or by artificial means, are examined, and their situation, nature, and arrangement are recorded upon a topographical map. When sufficient information has been obtained, the boundary lines between each recognisable stratum or series of strata can be completed; see *Fig.* 36.

In a geological map the areas occupied by the various formations, or by their sub-divisions, are indicated by means of colours or by conventional symbols. For example, in the official geological maps, and in most unofficial geological maps of this country, the outcrop of the Carboniferous Limestone is represented by a certain shade of blue, the outcrop of the Chalk by green, and those of the various members of the Oolitic series by shades of yellow. On large-scale maps (six inches or more to the mile) where much more sub-division of the rocks is possible, there will be a correspondingly greater number of colours.

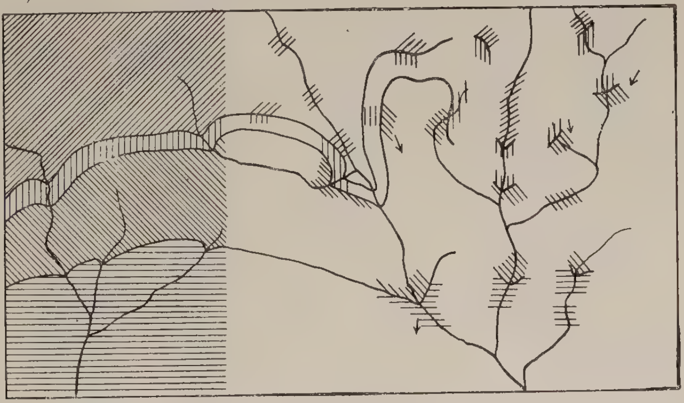

FIG. 36.—THE PREPARATION OF A GEOLOGICAL MAP.

On the right of the diagram, symbols have been inserted where various kinds of rock are seen in the banks of streams; in the central portion, similar evidence has been used to draw lines representing the edges of the outcrops of the various strata where the rocks are not actually exposed; and on the left, the map has been completed by drawing the symbols selected to represent the four strata concerned, over the whole of the area which each occupies.

In using a geological map it is necessary to bear in mind that a given colour indicates the areas occupied by rocks of the *same age*, but it does not necessarily imply that one and the *same kind* of rock will be found over the whole area. Failure to recognise the significance of their colours and symbols often gives rise to wrong conceptions concerning the value of geological maps, and results in waste of time when new sources of supply are being sought for. A blue tint, for instance, is used for the rocks that occur between the Old Red Sandstone below and the Millstone Grit above—that is to say, for the Carboniferous Limestone series—but it is a well-known fact that the Carboniferous Limestone includes many different rock-types, as is illustrated in *Fig.* 31, from which it will be seen that while at Ruthin, in Glamorgan, the rocks comprise oolitic, dolomitic and fossiliferous limestones, when traced eastward the dolomite increases in importance to the exclusion of the other types, until at Cefn On, about twelve miles away, the strata at the corresponding geological horizons are all dolomitic. The Chalk, on the other hand, was deposited under conditions different from those which existed in the Carboniferous Limestone sea, and the rock is much more uniform in character, both vertically and horizontally, with the result that the tint representing the upper part of the Chalk, on the one-inch geological map, indicates not only rocks of the same age, but, within certain limits, rocks of similar character.

On an ordinary geological map, lithological variations such as those just described as occurring in the Carboniferous Limestone could not be shown, and one colour would be used over the whole outcrop, but for regions that have received special attention—and they are many—more detailed maps, sections, and descriptions are available. The results of such research are usually to be found in the Journals and Transactions of scientific societies, such as the Geological Societies of London, Yorkshire, Manchester, Liverpool and Glasgow, and the Geologists' Association of London.

The relative ages of the rocks in the area depicted by a geological map are indicated in a *Table of Strata*—a list of the strata with the oldest (usually) at the bottom and the newest at the top—while the geological structure of the district is often indicated by means of a section drawn to show the relation that exists between the rocks: such a section may be regarded as a representation of what could be seen on the sides of a deep trench cut straight through the district represented.

Geological sections comprise "*horizontal sections*" (see *Figs.* 37 and 38) and "*vertical sections*" (see *Figs.* 31 and 68), although both are really vertical sections: the difference between them lies in the fact that whereas a "horizontal" section depicts the rocks of an extensive tract to a comparatively small depth, and shows the form of the ground and the structure of the region traversed, a "vertical" section represents, to a considerable depth, the strata of one locality, and is usually drawn as though the strata were all horizontal and undisturbed: vertical sections are convenient for showing how rocks of the same age vary in character from place to place. The relation between map, horizontal section, and vertical section is illustrated in *Fig.* 37.

The geological distribution of limestone.—Limestones are rare in the oldest rocks, and, on the whole, they become more and more conspicuous as newer rocks are encountered. It would, indeed, seem legitimate to conclude that with the passage of time limestone deposits have increased, both in abundance and in the width of their distribution. This is due to the fact that the lime is, in the first instance, set free as a result of the decomposition of igneous rocks, many of which represent material brought from the heart of the earth's crust, and each new area of igneous rock exposed to denudation by the removal of the strata above and around it adds to the supply of lime available for limestone formation.* The lime, as we have seen, passes into solution and

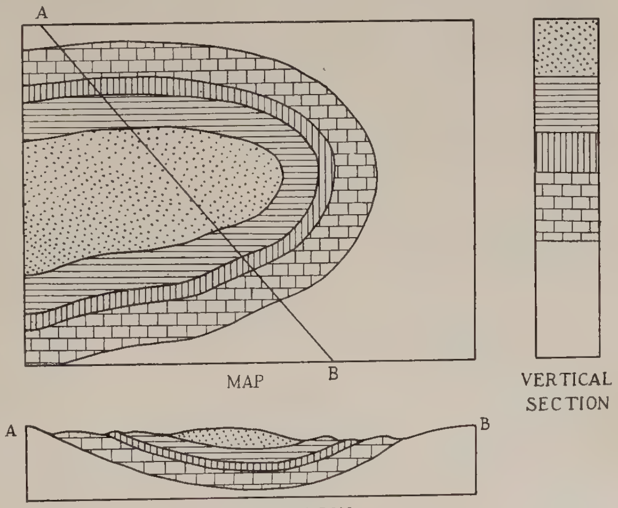

FIG. 37.—Geological maps and "sections."

Map and sections illustrating the relation between a geological map, a "horizontal" section (showing the geological structure of the area), and a vertical section (showing the order and relative thickness of the rocks).

* Lime (CaO) occurs in granite to an average extent of about 1 per cent., in basalt to an average of from 7 to 9 per cent., and igneous rocks, considered as a class, contain about 5 per cent. of that substance.

is carried by rivers to the sea. It has been shown that the amount of carbon dioxide in sea water is much more than sufficient to keep in solution all the calcium carbonate dissolved in it, so that except under special conditions, to which reference has already been made, the lime would remain in solution unless extracted by vital forces. In other words, we owe nearly all our limestones to the work of animals and plants, whether their remains are visible in the rock or not.

We are now in a position to understand the scarcity of limestone in the oldest—the Pre-Cambrian and Cambrian—strata. In the first place there would have been but little lime in the earliest oceanic waters, and but few animals to extract it. The scarcity of dissolved lime salts would be accounted for by the fact that the decomposition of the silicate minerals of the crystalline rocks of the surface of the primitive earth had not then proceeded far, for such decomposition would not commence until the condition of the earth permitted the condensation of moisture, and the formation of rain, rivers, and oceans. Living things, too, were in their infancy, for although some traces of fossils have now been discovered among the earliest (Pre-Cambrian) rocks, there cannot have been more than a very sparse fauna and flora. That animals did exist in Pre-Cambrian times is, however, evident from the fossils found in the overlying Cambrian rocks. These, the oldest rocks in which fossils can be considered as abundant, contain representatives of many of the important animal groups, and thus indicate a long period of previous development and evolution [5-8].

The animals represented by Pre-Cambrian and the older Cambrian fossils include various lowly invertebrates (that is, animals without backbones), such as jellyfish, which are entirely soft bodied; worms, which do not as a rule secrete any hard parts; and some members of the crustacea and of the brachiopoda in which the shelly covering was of a horny character. In other words, not only were there few animals, but those that did exist were not of the kinds that in later days contributed largely to the formation of limestone deposits. The thin horny shells of the earliest brachiopods and crustaceans, and the feebly impressed marks and tracks of worms and other soft-bodied animals, have rarely survived the effects of the heat and pressure which have so completely changed most of the Pre-Cambrian rocks, with the result that those rocks are now practically unfossiliferous, and our knowledge of the early forms of life is disappointingly meagre.

With the passage of time, the amount of dissolved calcareous material increased, and the animals capable of incorporating it into their hard supporting structures, as a preliminary to the formation of limestone, also increased both in variety and in abundance; and since the decay of igneous rocks exposed by denudation has furnished continual new supplies of calcium bearing salts, the total amount of limestone in the world must have been steadily increasing; see Additional Note, page 445.

One eminent writer, R. A. Daly, has suggested that all the Pre-Cambrian and early Cambrian limestones were chemical precipitates, on the grounds that the small amount of calcareous salts then present in the sea water would have been thrown down as calcium carbonate owing to the action of the ammonium carbonate produced during the decay of soft-bodied organisms. This being the case, he urged, it was not until the development and denudation of land areas had proceeded sufficiently far to allow streams to bring down more calcareous material than would be precipitated in the manner described, that sufficient dissolved lime salts could accumulate in the sea water to permit of the construction of calcareous shells and skeletons by marine organisms [9].

In connection with Daly's suggestion, however, we have to remember that the Pre-Cambrian limestones are often associated with graphite, a crystalline form of carbon, and carbon points to organic activities. There are now good reasons for supposing that calcareous algæ played an important part in the formation of the very thick and extensive limestones in the Pre-Cambrian rocks (Grenville Series) of Eastern Canada, but that group of deposits is unique among Pre-Cambrian limestones [11, 12].

One type of organism, to the activities of which in connection with limestone-formation reference has not yet been made, is the minute bacterium. In obtaining their nourishment bacteria split up many compound inorganic substances and set free some of their constituents. Some bacteria, for example, cause the deposition of iron compounds, others of copper compounds; some set free sulphur, and others nitrogen. One living form, *Bacterium calcis*, is giving rise to a precipitate of chalk-like mud on the Great Bahama Bank off the Atlantic coast of the United States [10].

Since recent investigation points to the existence of bacteria in remote geological periods, it is more than likely that they, also, contributed to the building of some of the earliest formed limestones.

From the point of view of present day limestone-users it would be interesting to know why creatures first began to build up calcareous shells and skeletons, but a discussion of that problem is outside the scope of the present work. It may well be that during the process of feeding and the rejection of waste products, there was a tendency for the calcareous material (the proportion of which dissolved in the water was increasing) to accumulate as a waste product in the skin of certain creatures, and since the hardened external covering proved to be a protection against the attacks of predaceous animals, natural selection would favour the creatures so protected and would lead to an increased development of that particular character. In a similar way, soft-bodied creatures of the sea-anemone type may have developed strong calcareous supporting structures which would not only have given additional stability, but would have discouraged the attentions of carnivorous crustaceans and fishes.

It is, of course, impossible to make any quantitative estimates concerning the relative rate at which limestone formation has proceeded during successive geological epochs, because so many factors are concerned. It is probable that the weathering and decomposition of rocks was slower in the earliest times, because algæ, lichens, and other plants which assist in the destruction of rocks were then unimportant, if indeed they had come into existence at all; on the other hand, much larger areas of primitive crystalline rocks were exposed than at present. As the importance of one of these factors has increased, that of the other has declined, and all the time there has been a steadily increasing animal and plant population secreting lime salts, and providing the material for limestone formation.

Distribution of limestone in Great Britain.—On considering the conditions under which the different kinds of sedimentary rocks were formed, and the great variety in the rocks that constitute the geological succession in this country, it will be realised that the part of the earth's surface where Great Britain and Ireland now occur has seen many changes in geographical conditions. Sometimes it has been dry land, at other times a comparatively deep sea, and frequently it has been the site of the accumulation of vast quantities of shore and shallow water deposits. For this reason, limestone is not equally distributed throughout the strata, nor is the geological distribution of limestone similar to that in other regions where the succession of changes has been different.

In this country the principal limestone forming episodes occurred in the Carboniferous, the Jurassic (Oolitic) and the

Chalk Periods, although there were numerous other minor occurrences of limestone-forming conditions. In other places, the sequence is not the same: for example, the equivalent in Saxony of the English Chalk is a yellow sandstone; while the Tertiary rocks, which in this country contain but little calcareous material, have thick widespread limestone deposits in Northern Africa and Asia.

Owing to the comparatively simple geological structure of the British Isles (for a discussion of the origin and development of which reference must be made to the standard geological text books) the limestone areas are fairly well defined. A geological map sufficiently small and simple to reproduce in this volume would be of very little assistance to those interested in the origin and distribution of limestone, but the following notes might with advantage be read in conjunction with an ordinary atlas, or better still with the Geological Survey map of Great Britain and Ireland on the scale of 25 miles to the inch. This is an excellently produced map showing the distribution of the principal rock formations of the country, and it costs only two shillings. It can be obtained from any agent for the sale of Government publications or Ordnance Maps.

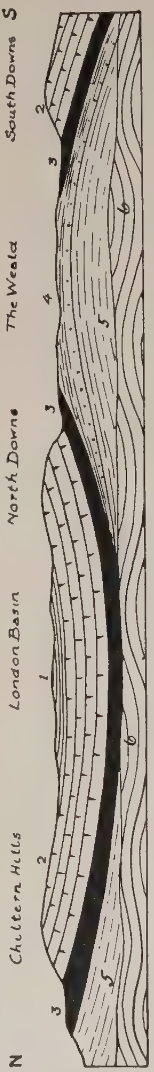

FIG. 38.—THE LONDON BASIN AND THE WEALD.

Diagrammatic section, not to scale, illustrating the geological structure of the London Basin (a synclinal fold) and the Weald (an anticlinal fold). 1. Tertiary rocks of the London Basin. 2. Chalk. 3. Upper Greensand and Gault Clay. 4. Wealden Beds. 5. Jurassic rocks, known to exist beneath the Weald. 6. The floor of folded Palæozoic rocks upon which the Mesozoic and later strata were deposited.

Disregarding small and isolated occurrences, the Chalk occurs south and east of a curved line drawn from Flamborough Head in Yorkshire to Lyme Regis on the south coast, by way of the Wash, where its outcrop is interrupted by the sea and by the superficial deposits of the Fen country. This great triangular area is further interrupted by the outcrop of the Tertiary rocks of the London Basin and of the older Cretaceous rocks of the Weald; the Chalk is continuous beneath the London Basin which has a synclinal structure, but is absent between the North Downs and the South Downs, for the Wealden area has an anticlinal structure (*Fig.* 38).

North and west of the Chalk area are the outcrops of the Oolitic and Liassic rocks, which extend from the north of Yorkshire to the south coast of Devonshire. The belt of country

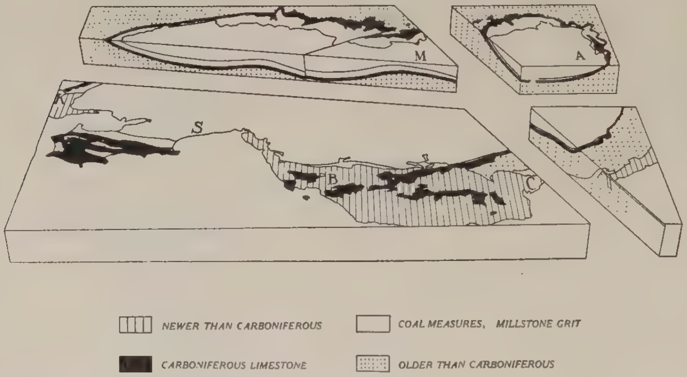

FIG. 39.—THE STRUCTURE OF THE SOUTH WALES COALFIELD.

A dissected model of part of the South Wales coalfield. The Carboniferous strata occupy a basin-shaped fold, complicated by minor folds and faults, and the coalfield is almost completely encircled by a narrow band of Carboniferous Limestone.
M, Merthyr; S, Swansea; B, Bridgend; C, Cardiff;
A, Abertillery.

occupied by those strata varies in width; it is widest in the north of Yorkshire and in the midlands, and it includes the outcrops of several economically important limestones, such as the Portland Stone, the Bath Stone, and the Lincolnshire Limestones.

The limestones of the Palæozoic Formations are, for the most part, less continuous in their outcrops. The Magnesian Limestone of the Permian System, and also the Carboniferous Limestone, trend generally north to south from Northumberland to Derbyshire, following the main structural features of the northern counties. In South Wales and Devonshire, where the folding is in an east to west direction, there are outcrops of Carboniferous Limestone encircling the South Wales Coalfield (*Fig.* 39), and of Devonian limestone in the south of the county after which that formation has been named. The Carboniferous Limestone is also present in Ireland, where, however, much of its outcrop is concealed by superficial deposits: it is also represented in the Isle of Man. There are small but interesting limestone deposits in the older rocks of the north of Scotland, of Wales, and the west of Ireland.

It will thus be seen that a considerable proportion of the area of this country is occupied by limestone or by sedimentary rocks containing more or less calcium carbonate, and, owing to the many varieties present, there are limestones available for practically every use to which the rock is put, with the exception of white crystalline marble for statuary and monumental work.

In the ensuing chapters it is proposed to describe the limestones of Great Britain and Ireland and to refer to the principal types found in each of the Geological Formations, whether they are of economic importance or not, but, naturally, it will not be possible to enumerate every locality in which limestones occur. It is obvious that the more extensive the deposit the less the detail in which it can be discussed, and on this account it may appear that undue prominence has been given to limestones that are of limited distribution or of minor importance. This, however, is not really the case, for the literature relating to such rocks is very scattered, and it is convenient to have it summarised in one publication: the lists of references will direct to sources of information relating to the more important occurrences. Similarly, where a matter of little more than academic interest has been discussed in some detail, such a course has been adopted on account of the opportunity it afforded of referring to an important principle.

It is also necessary to bear in mind that in discussing the properties of the various types of limestone found in this country, *kinds of rock,* and not the products of individual quarries, are being considered. Many quarries are intermittent in working and no useful purpose would be served by citing specific examples: information relating to all quarries over twenty feet deep that are actually in work will be found in the "List of Quarries" (Mines Department) issued annually by H.M. Stationery Office.

That many of the illustrations are drawn from localities in Wales and the west country is due to the fact that the writer is more familiar with the rocks of these regions than with those of the east and the north, but since, whether verbal or pictorial, the illustrations relate in most cases to general principles, the reader should have no difficulty in applying them to the conditions of other areas.

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PART II.

DISTRIBUTION OF LIMESTONE IN THE BRITISH ISLES.

CHAPTER IV.

LIMESTONE IN THE PRE-CAMBRIAN AND CAMBRIAN SYSTEMS OF ROCKS.

> "Immediately the mountains huge appear
> Emergent . . . their tops ascend the sky:
> So high as heaved the tumid hill, so low
> Down sunk a hollow bottom, large and deep."
> MILTON, in "*Paradise Lost*," Book VII.

The Pre-Cambrian Rocks.—The rocks of the Pre-Cambrian system are in many respects peculiar, and their discussion must, of necessity, be along somewhat different lines from that of the strata belonging to the more recent geological systems.

The Pre-Cambrian rocks constitute the floor upon which all more recent strata have been deposited, and they only occur at the surface in places where a vast amount of denudation has taken place; usually the outcrops are quite small, but in some parts of the world they occupy very large areas. Owing to the extent to which the rocks have been altered by metamorphic action, and to the general absence of fossils, it is extremely difficult to compare and correlate the rocks of one Pre-Cambrian outcrop with those of another, and for present purposes it will be convenient to consider them according to their geographical distribution.

Taken as a whole, the Pre-Cambrian rocks include a lower series of crystalline (but not exclusively igneous) rocks, and an upper series of sedimentary rocks—often much altered; frequently there is a middle series comprising rocks of volcanic origin. They indicate a period of time probably as long, if not longer than all the succeeding geological ages put together; for even the lowest (*i.e.*, the oldest) crystalline rocks include gneiss and schist representing sedimentary rocks that had been deeply buried, metamorphosed, and again exposed by denudation quite early in Archæan times. Upon this ancient floor, shales, sandstones, and occasional limestones were deposited, and at some time during the accumulation of the sediments there was a period of intense volcanic activity, during which lavas were poured out on the sea floor and explosive outbursts gave rise to beds of volcanic dust. All this vast accumulation of rock was crushed and folded during periods of earth-movement—mountain masses were built up and then reduced by denudation almost to the condition of a level plain—before the commencement of the Cambrian period.

It is, therefore, not surprising to find that all the limestones of Pre-Cambrian age in this country have been converted into crystalline marbles, or else are so crushed as to be useless for any practical purpose. A few of the marbles have been used for building and ornamental work, and, if their existence were more widely known, might again be used, but taken as a whole the scientific interest of the Pre-Cambrian limestones is greater than their economic value.

Limestones of Pre-Cambrian Age.—Limestones do not appear in any of the English Pre-Cambrian outcrops, but they occur in North Wales, the north-west of Scotland and in the west of Ireland.

Those in Anglesey have been fully described by Dr. E. Greenly in his great work on the geology of that Island [1]. He recognised various types of limestone, including (*a*) massive bluish-grey rocks, sometimes oolitic and sometimes pisolitic, (*b*) rose coloured and greenish coloured crystalline limestones, and (*c*) rocks that may be called serpentine marbles, or ophicalcite.

The rose coloured limestones are hard saccharoidal* rocks, usually dolomitic, and sometimes sparkling in appearance from the presence of minute spangles of mica. They owe their pink tint to the presence of manganese in the form of the mineral rhodochrosite—a carbonate of manganese, corresponding to a calcite, the carbonate of calcium, and dolomite the carbonate of both calcium and magnesium. They are frequently associated with jasper, and are seen to advantage at Garth Ferry on the Menai Straits, and at Llanddwyn, near Newborough. Some varieties are veined with quartz, others have a greenish tinge owing to the presence of the mineral chlorite, and others are beautifully brecciated.

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* That is, of a crystalline character, resembling lump sugar in appearance.

White crystalline marbles of striking appearance are found at Bodwrog, near the centre of the Island, and at Erddreiniog, while near Rhoscolyn, in Holy Isle, there are outcrops of serpentine marble or ophicalcite; this is a rock of striking appearance in which white crystalline calcite is associated with green serpentine (*Fig.* 40). It may be banded or brecciated, and is found to pass into marble with silicate-minerals* such as tremolite and talc.

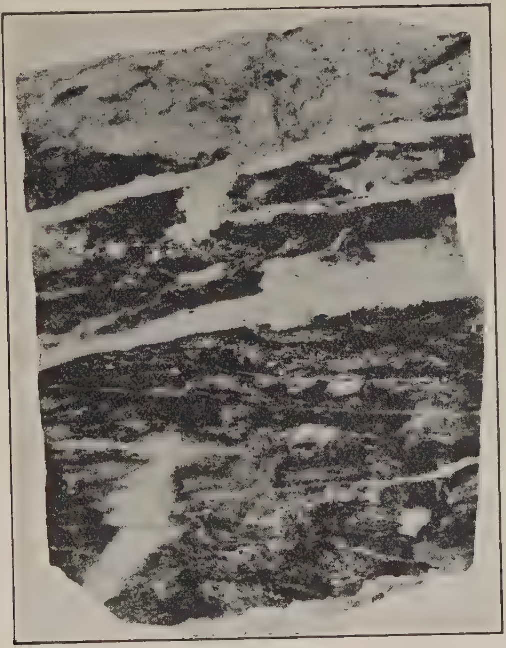

FIG. 40.—SERPENTINE MARBLE (OR OPHICALCITE) FROM RHOSCOLYN, ANGLESEY.

The rock is of a mottled green colour with white veins and streaks; about one-half natural diameter.

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* "Silicate minerals" is a convenient term for designating those minerals that consist of one or more metallic oxides combined with silica. They are by far the most important and most abundant rock forming minerals, and include varieties such as mica, hornblende, the pyroxenes, the garnets, and the felspars.

The ophicalcite is associated with serpentine* from the alteration of which it has resulted by a process of calcification, and Professor Bonney suggested that the calcium carbonate was introduced by infiltration from beds of Carboniferous Limestone which once covered the serpentine, but which have long since been removed by denudation [2].

Like the associated serpentine, the ophicalcite has been worked as an ornamental stone for church decoration, but none has been quarried in recent years. Near Aberdaron, at the end of the Lleyn Peninsula of Carnarvonshire, there are pink dolomitic limestones associated with jasper, resembling those at Garth Ferry and Newborough in Anglesey. The rock exhibits shades of pink, mauve, and heliotrope, is hard, and capable of receiving a high polish. It has been used in slabs for internal decorative purposes, as for example, in the entrance of the Empire Theatre, Cardiff, and in a building at the south corner of St. James' Street, Piccadilly, London, but the quarries are not at the present time in operation.

The Pre-Cambrian rocks of Scotland include a lower group (Lewisian) of crystalline rocks—gneiss† and schist—and an upper group (Torridonian) of sedimentary rocks, mostly of a sandy and conglomeratic character. In the following notes, some of the more important limestones are enumerated, and for further information reference should be made to the appropriate Geological Survey Memoirs [8-10].

Near Loch Maree there is a group of altered sediments through which the Lewisian gneiss was intruded; the sediments are now represented by schists and altered limestones, and the latter are probably the oldest known limestones in Britain, or indeed in Europe. The limestone bands are from three to thirty feet in thickness, and include the cream coloured *Letterewe Limestone,* which has, in the past, been quarried, and the *Ardlair Limestone,* which is white and dolomitic.

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* Serpentine is the name given to rocks, consisting largely of hydrated silicate of magnesia with silicate of iron, that have resulted from the alteration of igneous rocks in which iron and magnesium bearing minerals, such as olivine, are particularly abundant. The change probably took place under the influence of heated water when the rock was situated deep beneath the surface of the earth, and before it was exposed by denudation.

The varieties of serpentine usually exhibit shades of green, variously mottled and often banded or speckled with red: the rock is comparatively soft and has a peculiar greasy lustre.

† Gneiss is a crystalline rock consisting, typically, of minerals similar to those of granite (namely, quartz, felspar and mica, but it differs from granite in having its minerals arranged in layers or bands. The layered structure may, in some cases, be due to the movement of the material when in a semi-molten state, and in other cases it is regarded as the effect of extreme pressure, after consolidation, upon a rock that would otherwise have been a granite.

The *Appin Limestone* of Argyllshire is about 100 feet thick, and is seen to pass through a sandy calcareous rock into quartzite (an altered sandstone).

Another important limestone is the *Ballachulish Limestone,* which, near Ballachulish, on the shores of Loch Leven, is a white crystalline marble with grey mottled patches. In other places the corresponding rock has somewhat different characters, and has received local names, as for example the *Islay Limestone* of Eastern Islay. In the Island of Iona, in the Inner Hebrides, there is a limestone (*Iona Marble*), which, although variable in character, has for the most part a pure white calcareous ground mass, veined and mottled with greenish yellow serpentine. It is an altered dolomitic limestone in which some of the magnesia has united with silica to produce silicate minerals that subsequently passed into the condition of serpentine; it may thus be compared in character, although not in origin, with the ophicalcite of Anglesey. The Iona Marble has for long been quarried, but not continuously, as an ornamental stone. It was used in the thirteenth century Cathedral of St. Mary in Iona, and more recently for church decoration in Scotland and elsewhere (Crathie Church, near Balmoral; Chapel of the Thistle, St. Giles Cathedral, Edinburgh; Crown Court Presbyterian Church, and Westminster Cathedral, London) [9].

A beautiful variety of marble occurs in association with the gneiss of the Island of Tiree in the Hebrides. It is a pink rock with dark green crystals of coccolite (one of the lime-magnesia-iron silicates belonging to the pyroxene group of minerals).

In the Island of Skye, between Broadford and Terran, there are marbles of various colours and textures, representing altered limestones. Grey and pink varieties and a white statuary marble have been quarried, but although the stones were in demand a century or so ago, little has been raised in recent years.

At Lismore, opposite Mull, there are Pre-Cambrian limestones, dark blue in colour, finely crystalline, and containing cubes of the mineral pyrites. The *Lismore Limestone,* like many other Archæan limestones, is associated with graphitic schist. The rock is burnt locally in kilns of the ordinary conical type, yielding a yellow lime that is used principally in agriculture and occasionally for building purposes [10].

In Ireland there are white granular crystalline marbles, suitable for ordinary decorative purposes, around Lough Dunlewy about 30 miles west of Londonderry. One of the most interesting of the Irish marbles is the green *Connemara Marble* (also called *Irish Green* or *Galway Serpentine*) of Galway. It is a highly altered serpentinous limestone, resembling the ophicalcite of other regions.

The prevailing colour is green, various shades of which are seen in twisted bands, often interrupted by veins of white granular calcite. The marble appears to have been produced as a result of the intrusion of an igneous rock (diorite) into a group of deposits containing dolomitic limestones. The igneous rock introduced silica, which combined with some of the calcium and some of the magnesium, forming silicate minerals such as olivine, and these have subsequently been changed into serpentine. The rock has been quarried near Clifden in Galway, and has been used for all kinds of decorative work; examples are to be seen in the interior walls of the new buildings of the General Post Office (London), and in a number of English Churches (including the Cathedrals at Bristol, Truro, and Peterborough).

Although foreign marbles are, in general, regarded as outside the scope of this book, the Pre-Cambrian limestones of Ontario and Quebec call for passing reference on account of a former discussion concerning their mode of origin.

These rocks were found to contain curious aggregates of calcite and serpentine, arranged in alternate layers in such a way as to suggest that the serpentine filled flattened cavities in a calcite framework. Sir W. Logan, well known in this country for his work in the South Wales Coalfield in the thirties of last century, regarded the structure as of organic origin, and Sir J. W. Dawson considered it to be the massive skeleton of an organism related to the foraminifera which grew in thick sheets on the sea floor, and to which he gave the name *Eozoon canadense* (*Fig.* 41). Forms in which the arrangement of the two minerals is slightly different were regarded as belonging to other species [3].

Later investigations have shown that the structure only occurs in limestones that have been recrystallised as a result of the intrusion of igneous rocks, and it has even been seen in blocks of limestone that have been thrown out of the crater of Vesuvius, so that it is now generally accepted that the structure is a peculiar intergrowth of calcite and serpentine, and is of inorganic origin, having resulted from the metamorphism of impure limestones. The Eozoon structure does not commonly occur in the British Pre-Cambrian limestones that are associated with serpentine, although it has been observed in some of the altered Cambrian limestones of Assynt.

The marbles of the Carrara district in Northern Italy, so much esteemed by builders and sculptors, might also be mentioned here, because the determination of their age affords an example of the steady progress of geological knowledge.

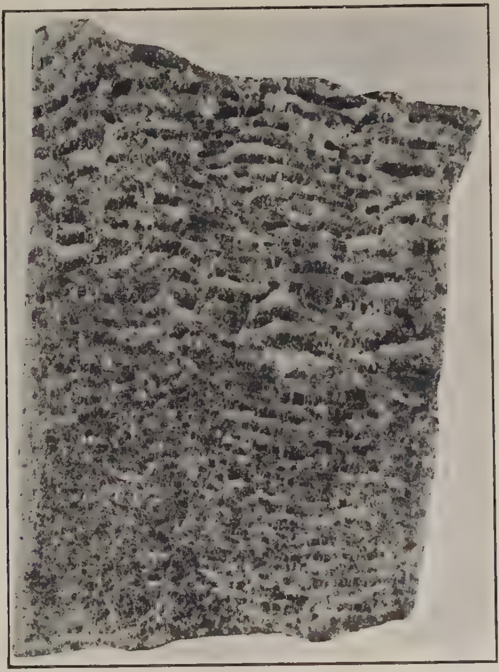

FIG. 41.—*Eozoon canadense*, DAWSON.

A banded variety of serpentine marble, formerly thought to be the skeleton of a massive form of foraminifera; twice natural diameter.

The marbles occur in an area where mountain building movements have effected profound changes in the condition and structural relationships of the rocks, and their age has, therefore, given rise to a great deal of discussion — successive writers tending to place them further and further back in the geological sequence. As far back as 1833, Savi, an Italian investigator, referred them to the Cretaceous series [11], but some years later the discovery of ammonites characteristic of the Lias of other regions was taken as indicating that the marbles were of Jurassic age, a view that for a long time was generally accepted; see for example, Murchison's classic memoir on the Geological Structure of the Alps [12]. A French geologist, Coquand, had, however, produced evidence suggesting that the ammonite-bearing strata rested unconformably upon the marbles, which, therefore, belonged to some older period, and when the Italian, Cocchi, discovered fossils of Carboniferous age in strata intimately associated with the statuary marbles it was thought that their age had been settled beyond doubt. As a result of still closer investigation it was felt by certain workers familiar with metamorphic rocks that the wholly crystalline marbles could scarcely be contemporaneous with the Carboniferous and Liassic strata that, although altered, still retained sufficient of their original lithological and fossil characters to be recognisable, and Professor T. G. Bonney held that the intimate structure and field relations of the marbles point to their being Archæan or Pre-Cambrian masses that owe their association with the newer strata to the effect of faulting [13].

The white statuary variety is by no means the only marble occurring in Tuscany, for the cloudy and mottled varieties known in this country as *Sicilian Marble* also come from some of the many hundreds of quarries with which the Apuan Alps are scarred. The origin of the term Sicilian is not known, but it is a misnomer because the rock does not come from Sicily. Well known instances of the use of Sicilian Marble are the Marble Arch, first erected in front of Buckingham Palace in 1827 and removed to its present site in 1850, and the memorial to Queen Victoria erected in 1912, also in front of Buckingham Palace. There are also many other Tuscan marbles, beautifully veined and coloured, a description of the appearance and applications of which would require a volume to itself [14]; examples will be found in most of the large museums.

The Cambrian System. — A great interval of time occurred between the formation of the newest Pre-Cambrian strata in this country and the deposition of the earliest Cambrian rocks. How long the interval was can never be determined, but it was sufficiently long, as we have seen, for the Pre-Cambrian rocks to have been folded during periods of earth-movement (*Fig.* 42), raised into lofty mountain masses, and then worn down almost to a level surface. It was on this denuded surface of Pre-Cambrian rocks

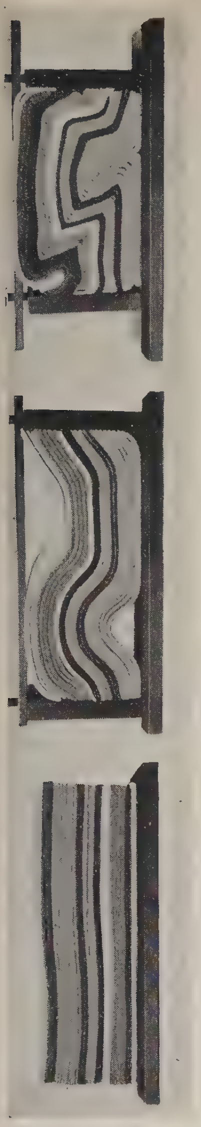

FIG. 42.—PHOTOGRAPH OF MODELS ILLUSTRATING THE FOLDING OF STRATA.

Layers of felt are used to represent a succession of horizontal strata, which, when laterally compressed, are thrown into folds, the intensity of which depends, other things being equal, upon the amount of compression.

that the earliest Cambrian sediments accumulated, when a regional depression again allowed the sea to occupy the British area.

Limestones are not abundant in the Cambrian rocks of England and Wales, but they are present in force in the North-West Highlands of Scotland. The reason for their absence from the south of Britain is two-fold—in the first place, it was a part of the Cambrian sea basin in which ordinary land-derived sediments were accumulating, the sediments being mostly sands and clays derived from a land mass that lay to the west of France and to the north-west of Wales, deposited in a sea covering the southern part of the British Isles and extending towards Scandinavia; while in the second place, the animals living in that sea were, for the most part, of kinds that either did not secrete skeletons or shells, or, if hard coverings were developed they were of a horny rather than a shelly character. This is the case, for example, with the trilobites, and with the brachiopod *Lingulella* which is abundant at certain levels in the Cambrian rocks.

There was an area of clear water in the north of Scotland, for limestones were deposited in that region as a result of the activities of shell secreting animals—mainly members of the Mollusca. In lithological characters and fossil contents the Cambrian rocks of the north-west of Scotland are more like deposits of similar age in North America than like the Cambrian strata of the rest of this country. Indeed the resemblance is sufficiently close to suggest that the deposits of both areas must have accumulated under exactly similar conditions, probably in different parts of the same water basin [4].

There would appear to have been a sea of clear water extending eastward from North America, and including the area now occupied by the Cambrian limestones of Scotland, but separated from the sea in which the Welsh and English Cambrian sediments were accumulating, by a barrier that prevented the molluscs of the northern sea from mingling with the trilobites and brachiopods of the southern sea. The barrier may have been a narrow tract of land, or it may have been a region of particularly muddy water, now represented by the Cambrian strata of the Lake District and of the Isle of Man, which are practically without fossils; for a stretch of muddy water would effectually stop the migration of animals that could only thrive in water that was clear.

It will be remembered that the Pre-Cambrian period was one during which shell-forming creatures were very rare, and that the rocks of the time have been so changed by metamorphic processes that most of their fossils have, as far as the strata of this country are concerned, been entirely obliterated. For this reason it is very difficult to compare and correlate the Pre-Cambrian rocks of one region with those of another, because, as we have already seen, fossils provide the most reliable means of determining the relative ages of rocks. In the Cambrian and later periods, however, fossils become increasingly varied and numerous, and the difficulties of correlation are proportionately less.

It has been found possible to divide the Cambrian rocks into well defined groups on the evidence of their fossils, particularly certain trilobites, which although not usually abundant, are widely distributed; and because of this it is possible to compare the Cambrian rocks of the various regions in which they appear from beneath newer strata. The discussion of their distribution and characters will be facilitated by introducing at this stage the names that are applied to the various sub-divisions of the System; they are given in *Fig.* 43. A similar course will be followed in the case of each of the Geological Systems that will be referred to in subsequent chapters.

Limestone in the Cambrian System.—Although the Cambrian rocks are well developed in Wales (indeed it was on this account that Adam Sedgwick (*Fig.* 44), the Cambridge professor and sturdy pioneer in geological investigation in this country, gave them their name in 1835), those of the type-locality do not call for further mention here, because no limestones are found among the slates, grits, and sandstones of which the formation there consists; the same applies also to the Lake District, where part of the *Skiddaw Slate* is of Cambrian age, to the Isle of Man, where the formation is represented by the *Manx Slates*, and to the south

FIG. 43.—DISTRIBUTION OF LIMESTONE IN THE CAMBRIAN ROCKS OF GREAT BRITAIN.

In the second column are the names applied to the subdivisions of the Cambrian System based upon the distribution of fossils, and in the remaining columns are the names applied locally to the rocks included in the System. Except in the case of Wales, where the names are introduced for comparative purposes, areas such as the Lake District, the Isle of Man, and Ireland, where there are no Cambrian limestones, are not represented in the table.

	Divisions based upon the distribution of trilobites	*Wales*	*Shropshire*†	*Warwickshire*	*N.W. of Scotland*
UPPER CAMBRIAN	*Shumardia* Series	Tremadoc Slates	Shineton Shales	Stockingford Shales	DURNESS LIMESTONES AND DOLOMITES
	Olenus Series	*Lingula* Flags	There is an unconformity between the Shineton Shales and the Comley Beds, and most of the middle part of the Cambrian System is missing.		
MIDDLE CAMBRIAN	*Paradoxides* Series	Menevian Beds Solva Beds*			
LOWER CAMBRIAN	*Olenellus* Series	Caerfai Beds*	Quartzite and Conglomerates COMLEY LIMESTONE Sandstones	Hartshill Quartzite with HYOLITE LIMESTONE	Grits and quartzite

* In North Wales the Solva Beds and the Caerfai Beds are represented by the Harlech Grits and the Llanberis Slates.

† In the Malvern region also, the upper part of the Cambrian System is represented by shales, and the lower part by sandstones (the Hollybush Sandstone), the *Paradoxides* Beds and most of the *Olenus* Beds being missing.

east of Ireland, where there are grits and shales similar to those in Wales.

In the Midland district, however, some of the Cambrian inliers include thin beds of limestone. Among these is the *Comley Limestone*—a rock so full of fragments of the trilobite *Olenellus* (*Fig.* 45) as to be regarded as a trilobite-limestone—which occurs in Shropshire, between the Wrekin Quartzite below and the Hollybush Sandstone above [5]. At Comley there are thin purplish-red sandy limestones, grey limestones, and black limestones with fossils, in a series of sandstones and conglomerates that have been extensively quarried. The Comley beds are especially interesting because they yielded the first Lower Cambrian fossils found in the Midland region; the discovery was made by Dr. C. Callaway, in 1877 [7].

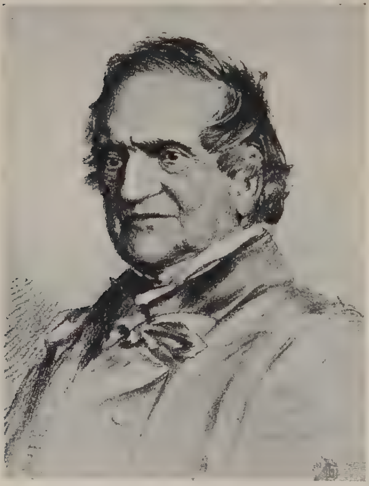

FIG. 44.—REV. ADAM SEDGWICK (1785-1873).

Woodwardian Professor of Geology at Cambridge, and founder of the "Cambrian System" of rocks; from a sketch made at the age of about 80. (Reproduced by permission of the Council of the Geological Society.)

There is also a thin (2 feet) band of red limestone of Cambrian age associated with the Hartshill Quartzite of the Nuneaton district. It is a hard tough rock containing numerous fossils, especially the shell known as *Hyolithus* (*Fig.* 43), and is seen in a quarry or cutting at Camp Hill Grange.

Although of great scientific interest, and of practical value in the correlation of the Cambrian rocks, these English Cambrian limestones have no commercial importance.

In the North of Scotland, the Cambrian system includes grits and sandstones in its lower part, but the upper part consists of limestone—the *Durness Limestone Series*—which is about 1,500 feet thick. The calcareous rocks are for the most part dolomitic, and in colour they are grey, white, or pink. They occur in the Durness area of Sutherland, and in the neighbourhood of Loch Eriboll [8].

The fossils, as already mentioned, are mostly shells with American affinities, while trilobites, which would enable the rocks to be correlated with those of England and Wales, are very rare; there is, however, sufficient evidence to show that the limestone corresponds in age to the Middle and Upper parts of the Cambrian system of the South, although by some it is believed that the uppermost beds belong to the Ordovician system. The most abundant fossils are members of the molluscan group, cephalopoda, but gastropods (univalved shells) and lamellibranchs (bivalved shells) are also important. The cephalopod group includes the *Nautilus*, of which there are both recent and fossil forms, and the Ammonites which are entirely extinct, but those represented in the Durness limestone were mostly straight shelled forms such as *Orthoceras*; see *Fig.* 64.

Although the Durness Limestone is very thick, the shells and shelly debris must have accumulated with extreme slowness (and, therefore, the Formation represents a long period of time) because the fossils show signs of having lain on the sea floor sufficiently long to have been partly dissolved before they were covered up. In most cases the external ornamentation has been lost, and internal structures such as those present in the cephalopod shells are rarely preserved.

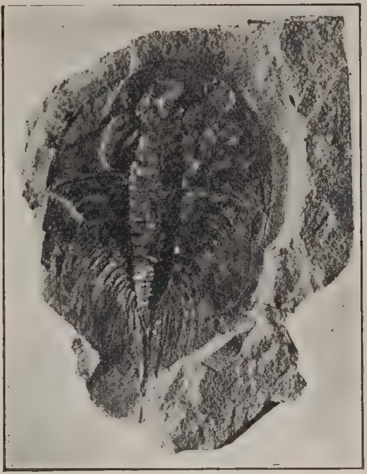

FIG. 45.—*Olenellus thompsoni* (HALL).

A trilobite from the Cambrian rocks of Pennsylvania; natural size.

An interesting feature of the Durness Limestone is that it contains layers of chert nodules and thin bands of chert (see page 259), recalling the flint nodules and bands in the much more recent limestone, the Chalk. Like the Chalk flint, the Cambrian chert contains fragments of sponge skeletons (sponge spicules), and they suggest the existence of similar conditions at two widely separated periods of time. The origin of flint and chert will be discussed in connection with the Chalk and other rocks in which they occur. At Assynt, and also in Skye, where the Durness Limestone has been invaded by igneous rocks, the former has, in part, been converted into crystalline marble.

Although used locally for building, the Cambrian limestones of Scotland have not at present proved to be of commercial importance. There are in places dolomitic varieties, but most of the dolomite used in connection with the Scottish steel furnaces is derived from the Magnesian Limestone of England, and although there must be vast reserves, the relative inaccessibility of the Durness rock does not favour its exploitation under present conditions.

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CHAPTER V.

LIMESTONE IN THE ORDOVICIAN AND SILURIAN SYSTEMS OF ROCKS.

> " . . . the *Ordovices*—a tribe as undaunted in its resistance to the Romans as the Silures; and if there is anything specially becoming in commemorating the warlike tribe of the Silures in the name of a geological system, how appropriate is the title of Ordovician in erecting a similar scientific monument to the last and most valiant of the old Cambrian tribes."
>
> C. Lapworth [1].

The Ordovician System.—We have seen that, except in the north-west of Scotland, limestones are not abundant among the Cambrian rocks of this country, partly because the area was one in which sandy and muddy sediments derived from the denudation of a land mass were being deposited, and partly because at that period in the earth's history animals and plants secreting calcareous supporting structures were not very abundant.

Similar conditions prevailed during the early part of the succeeding Ordovician period, but by " Llandeilo " times (see *Fig.* 46) not only was there an abundance of shell-bearing animals, but, locally, conditions favoured the accumulation of their remains in sufficient quantity to form limestones, or beds of highly calcareous sandstone and shale. Such rocks occur in several places and at various horizons among the Ordovician strata.

The sub-divisions of the Ordovician System.—Four main subdivisions of the Ordovician strata are recognised, namely, the Bala Series, Llandeilo Series, Llanvirn Series, Arenig Series (or Skiddaw Series), but owing to the varied characters of the rocks and of the fossils they contain, many local names are also used, and there is not universal agreement as to where the dividing lines between certain sub-divisions should be drawn. The names of the four principal " Series " are based upon the localities where the rocks included in them are best seen or were originally described; namely, Bala (in Merionethshire), Llandeilo (in Carmarthenshire), Llanvirn (in Pembrokeshire), Skiddaw (in the Lake District), and Arenig (in Merionethshire). The Bala Series is further sub-divided into an upper (Ashgillian) Series, and a lower (Caradocian) Series: the former name is derived from Ashgill in the Lake District, and the latter from Caer Caradoc, the chief mass in the Caradoc Hills of Shropshire, where the uppermost division of the Ordovician System is well developed.

FIG. 46.—Distribution of Limestone in the Ordovician Rocks of Great Britain.

Subdivisions of the Ordovician System	*Some of the Horizons at which Limestones occur.*					
	S. Wales	*N. Wales*	*Lake Dist.*	*Shropshire*	*S. of Scotland*	*Ireland*
BALA SERIES	Shoalshook Limestone, Robeston Wathen Limestone, Mydrim Limestone	Hirnant Limestone, Rhiwlas Limestone Bala Limestone	Coniston and Keisley Limestones, including *Staurocephalus* Limestone and Applethwaite Limestone			Chair of Kildare Limestone, Portraine Limestone
LLANDEILO SERIES	Llandeilo Limestone	Derfel Limestone		Limestone in the Meadowtown Beds	Stinchar Limestone	
LLANVIRN SERIES	The Ordovician rocks are mostly shales (or slates), sandstones, conglomerates, and rocks of volcanic origin (lavas and ashes). Limestones are practically absent from the Arenig and Llanvirn Series, but calcareous beds become more abundant and important in the higher strata, especially in the Llandeilo Series of South Wales, and the Bala Series in many parts of the country.					
ARENIG SERIES (or SKIDDAW SERIES)						

The Ordovician strata are more widely spread in this country than those of Cambrian age; they occupy large areas in West and

Central Wales, and are also found in Shropshire, Radnorshire, in the Lake District, in the south of Scotland, and in many parts of Ireland.

During Cambrian times the British area was part of a great oceanic trough that included the north of the present Atlantic Ocean and the site of the adjacent lands of Western Europe and North America. Now the study of rock-folding indicates that the accumulation of vast thicknesses of sediment in such troughs has usually been followed by earth movements on a large scale, resulting in a crumpling of the sediments, and often their uplift locally into the condition of dry land. A large trough may thus be divided into a number of smaller depressions, and the earth movements are often accompanied by volcanic activity.

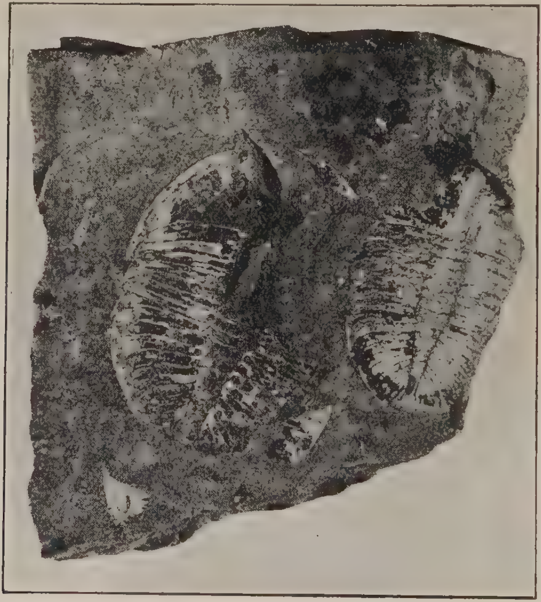

FIG. 47.—ORDOVICIAN TRILOBITES.

Ogygia buchi (Brongniart) from the Llandeilo Beds of Llandeilo, South Wales; natural size.

Foreshadowing the commencement of such a period of crustal movement, towards the close of Cambrian times the water became shallower in some places (for example in North Wales) and deeper in others, and similar conditions continued into the ensuing period, with the result that there are two fairly well defined types of Ordovician sediment—fine-grained material (now shales, mudstones, and slates) laid down in deep water, and sandy sediments with limestones laid down in shallower water, probably in the neighbourhood of volcanic islands that were formed from time to time. For this reason the Ordovician sediments of one region are often markedly different from those of other regions, and it is not always easy to compare them [2, 3, 4].

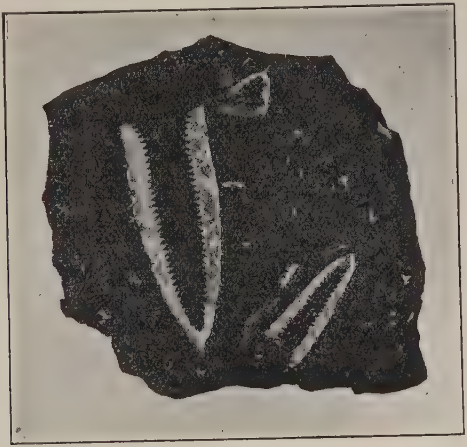

FIG. 48.—ORDOVICIAN GRAPTOLITES.

Didymograptus murchisoni (Beck) from the Llanvirn Beds of Abereiddy Bay, Pembrokeshire; natural size.

Limestones were deposited wherever the water was sufficiently clear, and in view of the conditions of accumulation of the Ordovician rocks—conditions determined by the local crumpling of the basin in which the sediments were being deposited—it will be realised that the calcareous beds will usually occur as lenticular (or lens-shaped) masses, at various levels within the System.

The most abundant fossils in the Ordovician rocks are trilobites (*Fig.* 47), graptolites (*Fig.* 48), and brachiopods; a few corals and polyzoa occur, and some genera of the mollusca are present. The members of the two first named groups are the most useful in the classification of the rocks, but the shells of brachiopods contribute most to the formation of the limestone bands of the System; trilobites are occasionally so abundant as to enter largely into the composition of some of the limestones, whilst the graptolites, which have a horny skeleton, are not limestone builders.

The rocks of the Arenig Series and the Llanvirn Series are mostly mudstones and shales (now slates), with sandstones, conglomerates, and much volcanic material (lavas and ashes); limestones are practically non-existent. On the whole, the Arenig rocks were laid down in shallower water than those of the Llanvirn Series, which, in the typical area, are dark coloured flags and slates with graptolites.

The Llandeilo Limestones.—During Llandeilo times relatively shallow water conditions again prevailed in South Wales, and the Llandeilo Flagstones and Limestones were deposited. These rocks take their name from the town of Llandeilo, where they are well displayed and have a thickness of about 2,500 feet. They are mostly thinly bedded calcareous flagstones associated with dark shelly limestones, and while they have been extensively quarried for building stone and road-stone, the limestones are, in this region, unsuitable for conversion into lime, and have not been burnt for that purpose.

Further west, between Carmarthen and St. Clears, the limestone occurs in discontinuous outcrops, often from 90 to 100 feet wide, and up to 300 yards long. It was formerly quarried for lime-burning at Clog-y-fran, near St. Clears, and its occurrence there and in various localities in Pembrokeshire was recorded by George Owen as long ago as 1595 [5]. The pains which Owen took to trace and describe the outcrop of the limestone in Pembrokeshire, and his account of the methods by which it was burnt and applied to the land, suggest that in his time the agricultural value of lime was more fully appreciated than it is now.

In Pembrokeshire, the Llandeilo Series includes earthy limestones and flags; the limestone beds, which range up to a foot in thickness, are crystalline; they are dark blue in colour when fresh, but when weathered are usually brown. They occur, and have been quarried, at Bletherston, Bullhook, Camrose, Crinow, Narberth and other places [6]. In this region, the Llandeilo limestones, as well as those of Bala age, make a good brown lime, which, because of its hardening properties, is very suitable for building purposes. The limestone at Bullhook is a blue-black well bedded rock, with vertical veins of white calcite lining joint fissures: it has been quarried for buildings and railway bridges.

Limestones of Llandeilo age also occur among the Meadowtown Beds of South Shropshire [7], in the Berwyn Mountains and in the Arenig Mountains, where the *Derfel Limestone* contains many fossils, especially brachiopods [8]. Impure limestones, some shelly and some saccharoidal, occur in the Llandeilo Series north-east of Llanrhaiadr-ym-Mochnant in Denbighshire. The rock was quarried for reservoir construction in connection with the Vyrnwy (Liverpool) Waterworks scheme, and has been burnt for lime [9].

Small lenticular masses of limestone also occur in beds of Llandeilo age at Port Padrig in Anglesey, but apart from those in South Wales, the Llandeilo Limestones are not of economic importance, and are only mentioned here in order to emphasise the wide occurrence of limestone-forming conditions at certain times during the Ordovician period.

In the south of Scotland, the *Stinchar Limestone* (so-called from the river of that name which enters the Firth of Clyde near Ballantrae), which is associated with shales and sandstones of Llandeilo age, is of interest, because, like the (Cambrian) Durness Limestone in the North-west Highlands, its fossils are more closely allied to those found in beds of similar age (the *Trenton Limestone*) in North America, than to those of the Ordovician rocks in other parts of Great Britain.

Some of the beds are hard, compact and nodular, and others are well laminated. The former are dark in colour when fresh and have veins of white calcite, and were at one time much quarried for lime-burning and wall building; the latter are very impure and of little use economically. The Stinchar Limestones have, locally, been much affected by earth movement and igneous intrusion [10].

The Bala Limestones. — Limestones are more extensively developed in the upper (Bala) division than in the lower divisions of the Ordovician System, and they occur in South Wales, North Wales, the Lake District, and Ireland.

In South Wales, the Bala Beds are for the most part shales, sandstones, and mudstones, but limestones occur at a few horizons —usually, as already mentioned, in lenticular beds that thin out in all directions, but which reappear elsewhere at corresponding geological horizons. The principal limestones have been given local names—*Shoalshook* (or *Sholeshook*) *Limestone*, *Robeston Wathen Limestone*, and *Mydrim Limestone* — from the places where they are best developed. The two first named are well displayed near Narberth, and are more widely distributed than the Mydrim Limestone.

In the country to the north-west of Ammanford, in Carmarthenshire, the Bala Limestones, which have an aggregate thickness of about 200 feet, are dark grey crystalline rocks, very fossiliferous, and sometimes sandy. They have been quarried near Llandeilo for lime-burning : in this they differ from the somewhat older Llandeilo Limestones of that district, which are more suitable for building stones.

Nearer to Carmarthen, the Bala Limestone forms the crags upon which stand the ruins of Dryslwyn Castle. The Dryslwyn Castle Hill is of particular geological interest, because, owing to faulting, all the shales and sandstones between the Bala Limestones and the Llandeilo Limestone are absent, and three distinct limestones make up practically the whole of the mass [11].

The Mydrim Limestone, named from Mydrim, about 7 miles west of Carmarthen, is a thinly bedded, dark grey, impure rock that has been quarried for lime-burning. The church at Mydrim stands upon a bluff of this limestone. A thin limestone (the *Castell Limestone*) occurs at a similar horizon at Abereiddy Bay, in Pembrokeshire; it is a fine grained massive rock, dark grey-blue when fresh, and, with the associated shales, is about 50 feet in thickness [12].

Other limestones occur locally in the West of Carmarthenshire and in Pembrokeshire at higher horizons in the Bala Series than the Mydrim Limestone, and there appear to be two distinct groups of calcareous beds—the Robeston Wathen Limestone and the Shoalshook Limestone. The former is the lower of the two, and they are, in the aggregate, about 300 feet thick. The Robeston Wathen Limestone is a comparatively pure blue-black, grey-weathering, tough rock, which has been burnt for lime at several places near Whitland. It contains many fossils, especially corals and brachiopods, but very few trilobites are present. The Shoalshook Limestone, which is greenish grey in colour, is evenly and thinly bedded and is usually sandy. It is often very fossiliferous, and it has been used locally for buildings, retaining walls and bridges. Its fossils are quite different from those of the Robeston Wathen Limestone and include many trilobites. At Llandowror, near St. Clears, limestones (more or less decalcified) of Bala age are quarried for roadstones (*Fig.* 49).

The Ordovician limestones in South Wales have been, to a considerable extent, "decalcified," that is to say, most of the calcium carbonate has been removed in solution, leaving a friable yellow sandstone or even a "rotten stone" (see page 48), representing the insoluble skeleton of the rock. In such cases the fossils occur as hollow moulds or casts and are very conspicuous. The decalcification is a result of weathering and affects the rock only near the surface: in borings, or when quarry operations have removed the weathered layers, the unaltered limestones are usually met with.

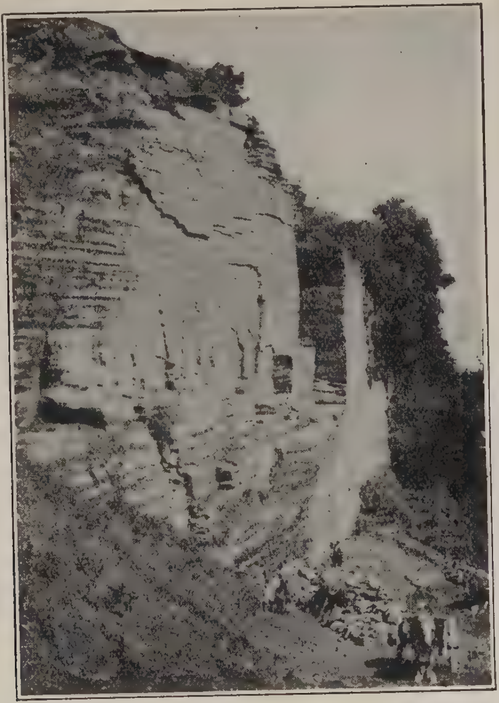

FIG. 49.—A QUARRY IN ORDOVICIAN LIMESTONE, LLANDOWROR, CARMARTHENSHIRE.

The wall-like character of the quarry-face is due to the development of strong vertical joints. (*Photo F.J.N.*)

Rocks of Bala age extend northwards and occur in many parts of Central Wales, but they are at present imperfectly known, and important limestones do not appear among them until North Wales is reached. Here, as in South Wales, the main "Bala Limestone" includes two distinct groups of calcareous beds, of which the upper, the *Rhiwlas Limestone* (named from Rhiwlas, north of Bala) is tentatively regarded as the equivalent of the Shoalshook Limestone of Pembrokeshire. The Rhiwlas Limestone is a pale grey fragmentary rock, not suitable for burning into lime. The lower limestone, or Bala Limestone proper, may be the equivalent of the Robeston Wathen Limestone. It is a dark grey crystalline rock, sometimes oolitic, and, unlike the Rhiwlas Limestone, is very pure, and has in the past been much worked for lime: the remains of old kilns are to be seen on nearly every outcrop.

In the Bala district, the aggregate thickness of the two limestones is from 20—70 feet, and they are split up by bands of shale and sandstone. They are very fossiliferous, and have been traced over a wide area. Only in one place, Bryn-pig, about two miles south of Bala, are both limestones present: as a rule only one of the horizons is highly calcareous, with the result that there has been a tendency to confuse them, but Dr. G. L. Elles has shown that they are distinct, and has called the lower or Bala Limestone proper, which is most likely the equivalent of the Robeston Wathen Limestone of South Wales, the *Gelli Grin Limestone*. Apart from the use of the Gelli Grin limestone for lime-burning, the Bala Limestones of this district are only suitable for rough buildings [13].

Above the Bala and Rhiwlas Limestones, and separated from them by a considerable thickness of sandy and shaly beds, is another thin limestone of local distribution, known as the *Hirnant Limestone,* which may perhaps belong to the bottom of the Silurian System rather than to the top of the Ordovician. It is a black, fossiliferous rock, exhibiting a pisolitic (see page 208) structure. Near the horizon of the Mydrim Limestone of South Wales, there are, in parts of Merionethshire, for example, near Dinas Mawddwy, black shales, with layers of calcareous nodules or thin beds of dark fossiliferous limestone [22, 23].

In the Berwyn Mountain region, the Bala Limestones are sometimes as much as 300 feet thick, and near Glyn Ceiriog, the Dolhir Beds, which are mostly slates and shales, contain groups of limestone beds, the most conspicuous of which is the *Dolhir Limestone;* this is often crowded with fossils, and is quarried in a few localities. Limestones (the *Pen-y-garnedd Limestone*), which with the associated shales and ashy beds are about 100 feet thick, occur in the upper part of the Bala Series near Llanfyllin and near Llangynog in Denbighshire and are quarried for lime [9].

Further north and north-west, the Ordovician strata do not contain limestones, although some of the volcanic ashes of Caernarvonshire are often noticeably calcareous, and calcareous ashes containing fossils occur near the summit of Snowdon.

In the Lake District also, limestones occur in the Bala Series of the Ordovician System. In the Cross Fell area there is the fossiliferous *Keisley Limestone*, a white crystalline rock, and in the neighbourhood of Coniston are the *Applethwaite Limestone*, and the *Staurocephalus Limestone* (so-called from its characteristic fossil, a trilobite). The *Staurocephalus Limestone* appears, from its fossils, to correspond to the Rhiwlas Limestone of Bala and the Shoalshook Limestone of South Wales. The group of beds in which the limestones occur is also known as the *Coniston Limestone Series*. Most of the limestones are hard, compact, dark blue rocks, but, weathering badly, they are not very suitable for use as building stones.

In Ireland, there are thick fossiliferous limestones of Bala age in Kildare, and a coralliferous limestone occurs at Portraine on the coast north of Dublin Bay. The *Portraine Limestone* is probably unique in its mode of origin, which is thus described by Jukes-Browne :—

> " A volcanic vent established itself in the Ordovician sea not far from Portraine and formed a volcanic island, from which many streams of andesitic lava were poured out from time to time. One of these flowed in the direction of Portraine, and its emission was followed by an explosive eruption which strewed quantities of blocks, stones, and fine ash over the surrounding sea-floor. . . . As these explosions and outflows of lava died away, beds of calcareous mud began to be deposited, and various kinds of marine animals found the submarine slopes of the island so favourable to their existence that their remains rapidly accumulated to form beds of limestone. At this time certain corals were so abundant as to form coral-banks, and one of these now appears as the ' coral-bed ' in the limestone " [14].

Taken as a whole, the limestones of Ordovician age are of greater scientific interest than present economic importance. For the most part they are impure, but they have been used for some purpose or other in most of the districts where they occur, and, in the past, when transport facilities were less developed, they were of considerable local value. They have been dealt with more fully than might appear necessary from their comparative unimportance, because the information relating to them is scattered, and difficult of access to the ordinary reader.

The Silurian System. — Like the preceding Ordovician and Cambrian periods, the Silurian was essentially a marine period. The conditions were, on the whole, similar to those during Ordovician times, except that there was practically no manifestation of volcanic activity in the British area. The ancient oceanic trough in which the Cambrian and Ordovician sediments were laid down continued to undergo crumpling, so that while in some areas the Silurian rocks are very thick, in others they are comparatively thin, but by the end of the period, the basin of deposition was practically filled with sediment, and shallow water conditions prevailed over most of the British area.

By Silurian times, lime-secreting animals had become much more varied and abundant, and wherever suitable conditions of deposition existed, limestones were formed on a larger scale than had usually been the case during the preceding geological periods.

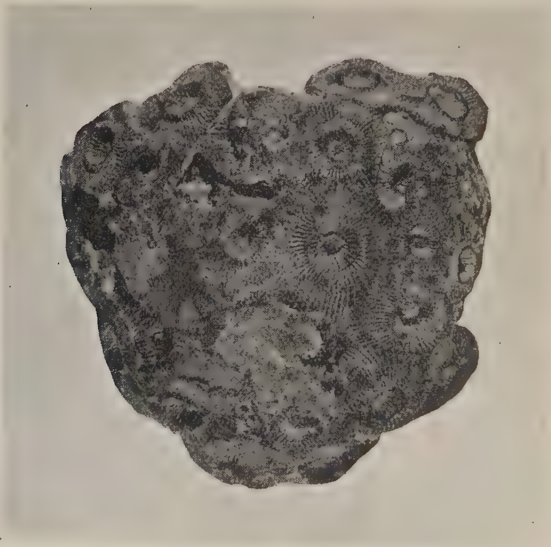

FIG. 50.—A SILURIAN CORAL.

Acervularia luxurians (Eichwald) from the Wenlock Limestone of Dudley; natural size.

Corals (*Fig.* 50), bryozoa, crinoids (sea-lilies), brachiopods, and molluscs (all of which secreted substantial supporting structures or shells, of which the principal inorganic constituent was calcium carbonate) were the dominant members of the animal kingdom; trilobites (*Fig.* 51) were also abundant, and there is evidence of the existence of many calcareous algæ. The graptolites, although of great use in correlating the strata, played no part in the formation of limestone; they reached their maximum during Ordovician times, and died out before the end of the Silurian period. Fishike organisms make their first appearance as fossils in beds ccurring near the top of the System.

The sub-divisions of the Silurian System.—For present purposes the threefold sub-division adopted by the older geologists s convenient, although the System has now been divided into a series of "zones," each characterised by its own assemblage of ossils, making it possible to compare in detail the rocks of one egion with those of another [4].

The succession is as follows :—

SILURIAN SYSTEM

(Old Grouping)		(Modern Grouping)
Ludlow Series	Downton Beds (Shales, "Tilestones," and sandstones)	*Downtonian* (by some authorities the upper part of the Downtonian is considered to belong to the Devonian System)
	Upper Ludlow Beds (Shales, mudstones, and sandstones)	
	AYMESTRY LIMESTONE (= Sedgley Limestone)	*Salopian*
	Lower Ludlow Beds (Shales and mudstones)	
Wenlock Series	WENLOCK LIMESTONE	
	Wenlock shales	
	WOOLHOPE LIMESTONE (= Barr Limestone)	
Llandovery Series	Tarannon Shales Llandovery Beds (Shales, sandstone and grits)	*Valentian*

The moderately shallow water conditions that prevailed at the close of the Ordovician period continued during the earlier (Valentian) part of the Silurian period, and the rocks are almost entirely conglomerates, sandstones, and shales (now in part converted into slate); but during Wenlock times two distinct types of deposit accumulated—(*a*) dark shales and mudstones in which the most characteristic fossils are graptolites, and which accumulated in deeper water than the other type, and (*b*) shelly shales, sandstones, and limestones of shallow-water origin, all of which accumulated in the neighbourhood of the shore-lines.

An examination of *Fig.* 52 in association with *Fig.* 53 will show that the limestones were deposited in the comparatively shallow water of the sea that, as Silurian times progressed, came to occupy the site of the peninsula that projected south-westwards at the beginning of the period [16]. Apart from the evidence of the associated sediments, the shallowness of the water in which the limestone was deposited is suggested by the abundance of corals, which are usually associated with moderately shallow clear water, and a fairly warm climate. The Ludlow Beds are mostly shales and sandstones, and they indicate the final silting up of the ancient oceanic trough.

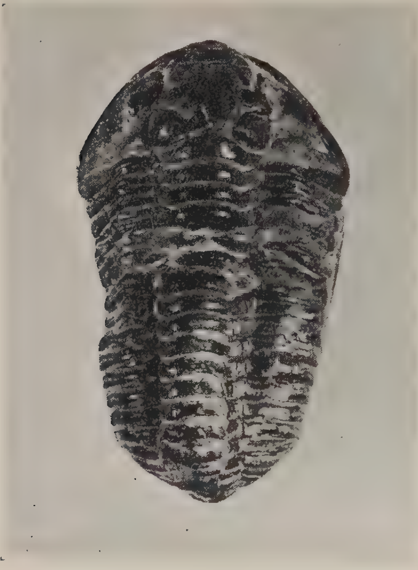

FIG. 51.—A SILURIAN TRILOBITE.

Calymene blumenbachi (Brongniart) from the Wenlock Limestone of Dudley; natural size.

The Silurian System was so named, in 1835, by Murchison (afterwards Sir Roderick Impey Murchison, Director General of the Geological Survey) (*Fig.* 54) from the Welsh borderland country — the territory of the ancient British tribe of the Silures; he included in his System, not only the rocks now called Silurian, but also those now referred to the Ordovician System. The former he called Upper Silurian, and the latter, Lower Silurian. Sedgwick, however, working upwards from the base of the fossiliferous rocks in Wales divided his "Cambrian System" into three divisions, the uppermost of which eventually proved to be equivalent to Murchison's Lower Silurian. This led to a long controversy—one of the bitterest in the annals of British geology—and eventually Charles Lapworth suggested that the intermediate strata should be regarded as belonging to a separate system, for which he proposed the name Ordovician, from an ancient British tribe—the Ordovices—that inhabited part of North Wales.

It should be borne in mind when consulting them, that, on account of this change in nomenclature, the Lower Silurian of the older geological works and maps is the Ordovician of to-day, and not the lower part of the Silurian System as at present defined.

Limestones in the Silurian System.—Over most of the British area the Silurian strata consist of conglomerates, sandstones, mudstones, shales, and slates, and while limestones are practically absent from the Silurian rocks of those areas (for example—S. Wales, N. Wales) where limestones are developed in the Ordovician System, they appear in force in the Welsh borderland country; and in this respect, the System is not typically developed in the region from which it takes its name.

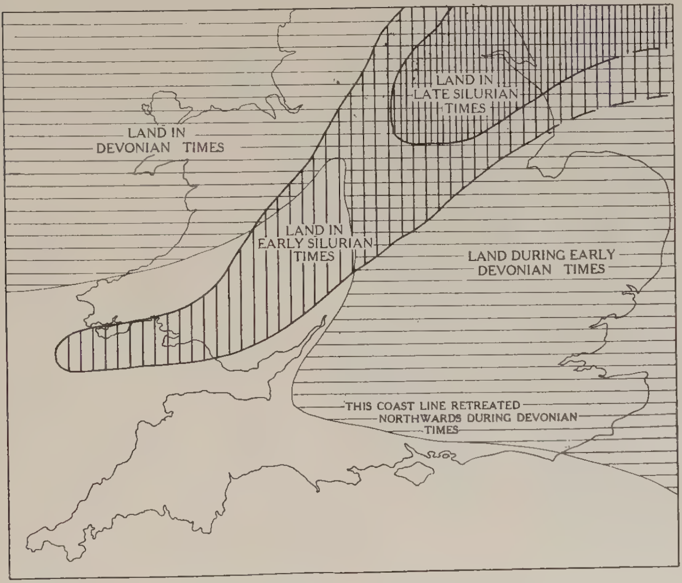
LAND IN LATE SILURIAN TIMES
LAND IN DEVONIAN TIMES
LAND IN EARLY SILURIAN TIMES
LAND DURING EARLY DEVONIAN TIMES
THIS COAST LINE RETREATED NORTHWARDS DURING DEVONIAN TIMES

FIG. 52.—MAP ILLUSTRATING THE GEOGRAPHY OF PART OF ENGLAND AND WALES DURING SILURIAN AND DEVONIAN TIMES.

Lines indicating the probable distribution of land and sea during the periods in question are superimposed upon a map of part of England and Wales. During Silurian times the area occupied by the sea tended to increase, but the Devonian period saw the development of an extensive land area.

The Silurian limestones are usually grey in colour, and they include crystalline, earthy, compact, and shelly varieties. For the most part they are very fossiliferous and wherever they occur they have been worked for some purpose or other—usually for cement making, lime-burning or as a flux, but also for road-stone and for building stone, although the rock is not usually obtainable in large blocks.

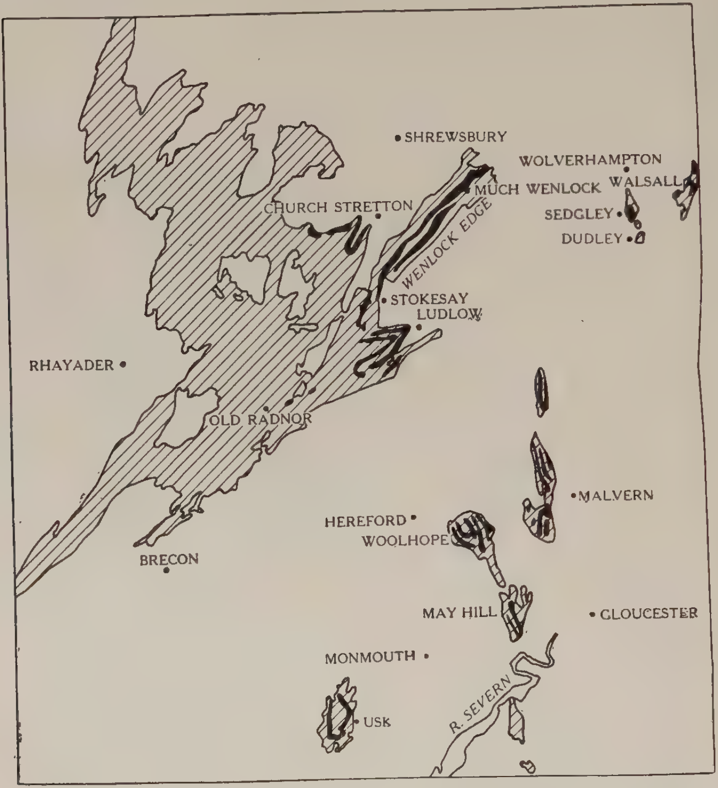
SHREWSBURY
WOLVERHAMPTON
WALSALL
MUCH WENLOCK
SEDGLEY
DUDLEY
CHURCH STRETTON
WENLOCK EDGE
STOKESAY
LUDLOW
RHAYADER
OLD RADNOR
MALVERN
HEREFORD
WOOLHOPE
BRECON
MAY HILL
GLOUCESTER
MONMOUTH
USK
R. SEVERN

FIG. 53.—MAP SHOWING THE DISTRIBUTION OF LIMESTONE IN THE SILURIAN SYSTEM.

The areas occupied by the Silurian rocks are indicated by close parallel lines, and the black streaks are the outcrops of the limestone. Scale, 1 inch about 20 miles.

In view of the limited distribution of the limestones, it is only necessary to consider the comparatively narrow region extending from a little south of the Wrekin in Shropshire to the neighbourhood of New Radnor in Radnorshire (a tract along which the Silurian rocks emerge from beneath the great Old Red

Sandstone region of Herefordshire, Brecknockshire, and Monmouthshire), and also a few small isolated patches, or inliers, in which Silurian strata have been exposed by denudation, in South Staffordshire, the Malvern Hills, around Woolhope, May Hill, and Usk, and near Cardiff.

It will be seen from the list of strata given above, that there are three main Silurian Limestones—the *Woolhope Limestone,* the *Wenlock Limestone,* and the *Aymestry Limestone*—but these are really more in the nature of local developments of limestone within the shales and mudstones, than continuous wide-spread deposits like the Carboniferous Limestone and the Chalk. Like the Ordovician limestones, they are really lenticular in form; each appears in considerable thickness in one place, thins out and reappears at a distance on approximately the same geological horizon. For example, when the Woolhope Limestone disappears, the shales above and below merge into one series that cannot satisfactorily be sub-divided; and where the Aymestry Limestone is not present it is difficult to assign limits to the Lower and the Upper divisions of the Ludlow Beds. In some of the inliers, one limestone only appears, as for example at Dudley (where only the Wenlock Limestone is seen), but in other cases two or all three limestones are present, as is the case at Woolhope and the Malvern Hills [21].

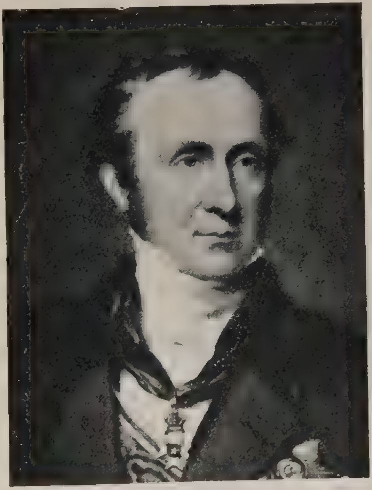

FIG. 54.—SIR R. I. MURCHISON, BT. (1792-1871).

Director-General of the Geological Survey, and founder of the "Silurian System" of rocks. (Reproduced by permission of the Council of the Geological Society.)

The Woolhope Limestone.—The Woolhope Limestone takes its name from Woolhope in Herefordshire, where an inlier of Silurian rocks emerges from beneath the Old Red Sandstone. In this region all three of the Silurian Limestones are present (see map, *Fig.* 53 and section, *Fig.* 55), and the Woolhope Limestone, the lowest, occupies a central position. It consists of dark blue

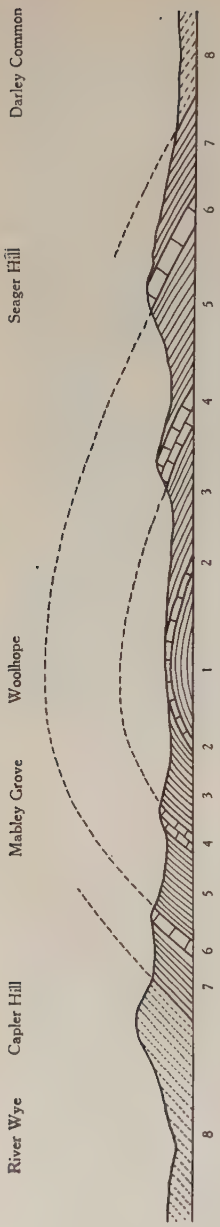

FIG. 55.—SECTION ACROSS THE SILURIAN INLIER AT WOOLHOPE.

Section after R. I. Murchison; horizontal distance about 6 miles, vertical scale exaggerated. 8. Old Red Sandstone. 7. Upper Ludlow shale. 6. Aymestry limestone. 5. Lower Ludlow shale. 4. Wenlock limestone. 3. Wenlock shale. 2. Woolhope limestone. 1. May Hill shales and sandstones.

nodular limestones, locally swelling into beds aggregating 30 or 40 feet in thickness, and is quarried at Woolhope and Ledbury.

The Woolhope Limestone also occurs in the Silurian inlier of Malvern; here it attains its thickest development (about 150 ft.), but it thins out northwards and eastwards. It is a rough impure limestone, very variable in thickness, but seldom actually missing; it is often nodular and is well jointed, and may consist of two or more limestones separated by sandstones, or it may appear as one thick bed. The outcrop, which is long and narrow, lies to the east of that of the Wenlock Limestone, and the rock has, in the past, been much quarried on a small scale [17].

The Woolhope Limestone is well exposed in the neighbourhood of Presteign and Old Radnor on the Radnorshire-Herefordshire border, where it occurs as a bluish-grey crystalline limestone which weathers grey or white and is apparently devoid of stratification; the last named character may be due either to its mode of accumulation, or to the crushing to which it has been subjected during periods of earth movement. It is very pure, containing over 99 per cent. of calcium carbonate, and it is not much broken up by shale bands. The limestone is fossiliferous, and in addition to an interesting suite of brachiopods, corals and mollusca, contains, in abundance, the remains of a calcareous alga, *Solenopora* (compare *Fig.* 24): the algæ occur in irregular growths, ranging in size from that of a pea to that of a potato, and are best seen on weathered surfaces; the memorial to the late Sir E. H. F. Lewis, in Old Radnor Churchyard, is a fine slab of algal limestone. In this region the Woolhope Limestone has been extensively quarried for a very long period, and it is still worked near Dolyhir Station and at Yat Hill; on account of its purity the stone was used principally as a flux in iron furnaces, and, when burnt into lime, for gas purification and agricultural purposes [18].

In South Staffordshire, the representative of the Woolhope Limestone is locally known as the *Barr Limestone*, from Great Barr near Walsall, where it is thin but very fossiliferous. The Barr Limestone has long been worked for lime-burning and other purposes, and it is practically worked out, its outcrop being marked by old and overgrown quarries.

The Wenlock Limestones.—The Wenlock Limestone is typically developed in the long ridge of Wenlock Edge, which extends in a south-westerly direction for nearly 20 miles from Benthall in Shropshire, and it has been quarried in many places. It is still worked at Much Wenlock, Presthope, Horton, and near Stokesay. It also occurs at the southern end of the Longmynd Hills, and is worked at Myndtown.

Although it has been extensively quarried, principally for lime-burning and as a flux (and, more recently, for cement-making, especially near Walsall) the Wenlock Limestone has acquired an importance out of all proportion to its thickness and extent, on account of the remarkable series of fossils it has yielded; this applies especially to the limestone of the small inliers at Dudley. Brachiopods, corals, trilobites, molluscs and polyzoa are all abundant—sometimes to such an extent as to make up the bulk of the rock—and fossils from the Wenlock Limestone are to be seen in practically every Museum in the world where geological specimens are preserved.

The Wenlock Limestone sometimes occurs as a single massive bed, but is more usually split up by two or more layers of shale. It is sometimes thinly and evenly bedded, but it is for the most part nodular in character, suggesting that the present distribution of the calcareous material within the shales is to a large extent due to local segregation or concretionary action: the probable origin of "concretionary" limestones will be further discussed in connection with those present in the Lower Lias (see page 186).

In colour the Wenlock Limestone is usually pale grey. Near Much Wenlock, a crystalline variety, somewhat dark in colour, has occasionally been used in small slabs as a "fossil marble," and an oolitic variety occurring near Ledbury has also been used locally for ornamental purposes under the name *Ledbury Marble.* While the rock at Much Wenlock has been used principally for lime-burning, that at Sedgley and Dudley has been quarried mostly for fluxing material.

There are two well-known localities for Wenlock Limestone near Dudley—Dudley Castle Hill, and the Wren's Nest—and the rock was called locally, "White Lime," presumably because of its somewhat lighter colour than the Barr Limestone (the local equivalent of the Woolhope Limestone) which was called "Black Lime." At the Wren's Nest there are two beds of limestone, an upper bed from 20 to 30 feet in thickness, and a lower bed from 35 to 40 feet in thickness, separated by about 90 feet of shale. The limestone occurs in two hills, each with a dome-like structure, and which, since the rock has been so extensively quarried, now present a peculiar appearance. There is a central mass of Wenlock Shale, with two encircling ridges of shale—one the shale that occurs within the limestone, and the other the Lower Ludlow Shale. Between these three shales are two more or less empty ring-like spaces from which the limestone has been removed. Where the dip is steep, the excavations form concentric moat-like hollows bounded by steep walls of shale, and where the dip is gentle, the limestone was followed underground, giving rise, both at Dudley Castle and the Wren's Nest, to extensive caves [19].

Although quarried for hundreds of years, the period of most active working of the Dudley quarries was comparatively brief. The cave-like workings were opened about 1830 to supply flux for the Dudley ironworks, and the output was so great that in less than ten years there were more than a mile of underground passages, some of considerable extent.

In 1839 the British Association visited Birmingham, and Lord Ward, then owner of both the limestone mines and the iron furnaces, arranged for parties to be shown over the workings which were specially illuminated for the purpose. Some were conveyed in boats (for the innermost workings were reached by means of an underground canal) and some travelled by foot along the passages, and when several thousands were gathered in the main cavern Murchison gave an account of his studies of the Silurian rocks. He was followed by William Buckland, then Professor of Geology at Oxford and afterwards Dean of Westminster, who for more than an hour lectured upon the origin of the surrounding country, and upon the animals represented by the fossils buried in its rocks. Similar underground workings from which rock is still being raised for cement making are to be seen at Rushall, near Walsall. The workable limestone (which is from 20 to 30 feet in thickness) is removed, and the shales below it form the floor of the artificial cave thus produced, while the shales above form its roof, which is supported by square pillars of rock left at suitable intervals. The old workings are very extensive and when they are illuminated by flares, the shadows cast by the "pillars" and the reflections in the water with which much of the floor is covered, produce an effect that is eerie in the extreme and enables one to visualise the conditions at Dudley when the scenes of 1839 were enacted.* The land surface over the area from which the limestone has been removed tends to collapse in places, giving rise to deep holes that resemble the "swallow holes" (see page 324) often produced as a result of the removal of limestone in solution. The details of the rock-succession are often clearly displayed around the sides of freshly formed subsidences.

Although used locally for rough walling, the Wenlock Limestone is rarely suitable for building purposes: it was, however, employed in Dudley Castle and in some churches, for example, that at Rushall, near Walsall.

In the Abberley Hills and the Malvern Hills the Wenlock Limestone group appears as two, three, or more beds separated by shales, including which it may be as much as 280 feet thick. It is usually smoky-grey in colour, and weathers yellowish, but in the extreme south, where it approaches the red Triassic strata, it is often pink or red, apparently owing to the infiltration of iron-bearing waters from Triassic rocks that once rested on it but have been removed by denudation; this phenomenon is further discussed in connection with the replacement of limestone by iron-ores (page 355).

The limestone bands form narrow elevated ridges, as for example, near Eastnor, where one band gives rise to the hill known as the Ridgeway. Formerly the Wenlock Limestone of the Malvern region was of great economic importance, as it supplied practically all the lime for the surrounding agricultural district; quarries and limekilns occur from end to end of the ridge, and, owing to the steep dip of the beds, the quarries were opened in narrow continuous lines along the crests of the hills. It is still quarried along the Abberley Hills between Martley and Astley.

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* For the privilege of visiting these works I am indebted to A. O. Vincent, Esq.; see also page 428.

A memoir by John Phillips (nephew and pupil of William Smith) contains some interesting information concerning the cost of the lime at the period, towards the middle of the last century (1848), when the Malvern quarries were being actively worked. The lime was sold at 8/- per ton, and the cost would have been less but for the high price of fuel; the usual proportion of fuel to rock was one to three or one to four. The lime-burner was capricious in his choice of stone, and he preferred the massive compact varieties to those which were thinly bedded. The lime was considered excellent both for building and for agriculture.

In the Silurian inlier around Usk in Monmouthshire, the Wenlock limestone includes a fairly pure massive limestone, consisting chiefly of coarsely crystalline calcite with fossils (mostly corals and crinoid fragments), and also nodular limestones. The rock was formerly burnt for lime, but is now quarried only for road-stone, as at Cilfigan Park. North of Glascoed there are old workings which, like those at Dudley, were continued underground, forming a series of picturesque caves. The rock quarried (or mined) was a pure massive limestone from 9 to 10 feet thick, and above it, roofing the workings, is a mudstone crowded with nodules of limestone [20]. In all these inliers, owing to the dome-like character of the folding, the limestone occurs in narrow curving outcrops.

Silurian strata also appear in a small inlier near Cardiff. The rocks are mostly mudstones and sandstones, but thin beds of limestone occur, probably representing the Wenlock and the Aymestry Limestones. At the surface, the limestones are, for the most part, de-calcified and they are of no economic importance.

The Aymestry Limestone.—The Aymestry Limestone is more local in its distribution than either that of Wenlock or of Woolhope. It occurs in the south-western end of the main Silurian outcrop in Shropshire, and also in some of the detached outcrops in Staffordshire and Herefordshire. It is thickest at Aymestry near Ludlow, where it varies from 30 to 40 feet, and it is thinnest where the Wenlock Limestone is best developed. It is usually a dark grey earthy rock, occurring in beds from 1 to 5 feet thick, and is very fossiliferous; some beds consist almost entirely of the remains of the large, almost globular, coarsely-ribbed brachiopod, *Conchidium knighti.* It is worked at Wigmore, Elton, Downton, and other places near Aymestry.

The Wenlock Limestone must have been deposited in fairly clear water, and during the time of the deposition of the Lower Ludlow Beds, which are muddy and sandy sediments, the lime-secreting organisms appear to have migrated to some other area, because, when the water again became clear, and the Aymestry Limestone was formed, the animals were essentially similar to those that lived in the Wenlock Limestone sea, although certain fossils, like the brachiopod *Conchidium*, already referred to, are regarded as characteristic of the Aymestry rock.

The equivalent of the Aymestry Limestone in the Sedgley district of South Staffordshire is known as the *Sedgley Limestone*, which is seen in the steep faced Sedgley Beacon; it is thicker but less pure than the Dudley Limestone, and although quarried, has never been extensively worked. In the Malvern district, the equivalent of the Aymestry Limestone is a calcareous shaly rock with nodules of limestone, not at all like the Aymestry Limestone of Shropshire. It is from 10 to 40 feet in thickness, and has no economic importance.

The uppermost Silurian strata are, in all localities, shales, sandy mudstones, and sandstones, indicating a general shallowing of the water owing to the filling up of the great oceanic trough that had occupied the region since early Cambrian times. This resulted from a gradual upward movement of the whole region—a movement that eventually converted much of the former sea into shallow bays or gulfs, and foreshadowed the commencement of the continental conditions that prevailed during the succeeding Devonian or Old Red Sandstone period (*Fig.* 56). The fossils of the uppermost Silurian rocks indicate that most of the organisms of the Silurian period had migrated to other regions, and very few marine animals remained; the principal inhabitants of the shallow muddy waters were the large scorpion-like creatures (Eurypterids) and primitive types of fish—the ancestors of those whose remains are so abundant in certain beds of the Old Red Sandstone.

Siliceous concretions — such as the flint nodules that occur in the Chalk and the "chert" that is found in the Carboniferous and Liassic limestones—are absent from the Silurian limestones and also from those of the Ordovician System.

Economically, the Silurian limestones are of considerably greater importance than those of the older formations in this country, and in a recent year the output of limestone from Herefordshire, Radnorshire, and Worcestershire was nearly 24,000 tons, all of which must have come from Silurian rocks; the output from Monmouthshire and Shropshire is difficult to ascertain, as Carboniferous Limestone also is quarried in those counties.

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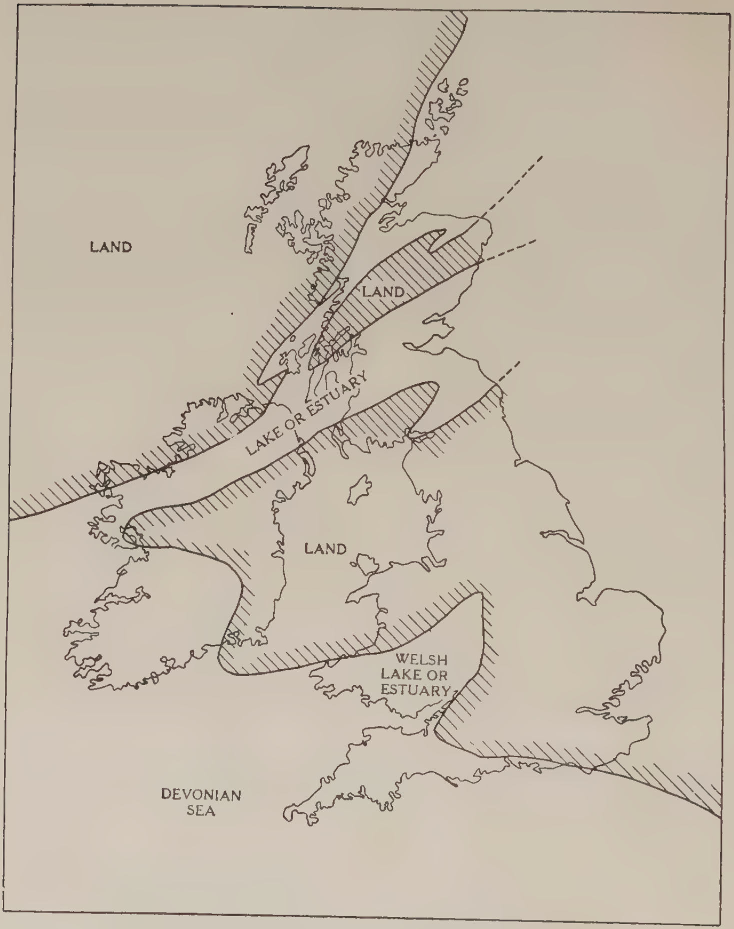
LAND
LAND
LAKE OR ESTUARY
LAND
WELSH
LAKE OR
ESTUARY
DEVONIAN
SEA

FIG. 56. — MAP ILLUSTRATING THE GEOGRAPHY OF THE BRITISH AREA DURING DEVONIAN (OLD RED SANDSTONE) TIMES.

Lines indicating the probable distribution of land and sea during part of the Devonian period are superimposed upon a map of the British Isles. Authorities are not agreed as to the existence of a narrow land barrier between the "Welsh Lake or Estuary" and the "Devonian Sea," forming a lake in which the Old Red Sandstone of Wales and the border counties was deposited. The marine limestones of South Devonshire were deposited on the floor of the open sea.

CHAPTER VI.

LIMESTONE IN THE DEVONIAN SYSTEM OF ROCKS.

> "Geology is the geography of the past. As the geographer . . . seeks . . . to produce a vivid picture of the physical features of some country, and to portray the characters and habits of the animals and plants which inhabit it, so is it the aim of the geologist to reproduce . . . the past physical features of the earth's surface, to restore the outlines of land and sea, to recall the positions of the mountains and valleys . . . and to re-people the several parts with the by-gone forms of the fauna and flora of successive periods."
>
> E. HULL, in "*Contributions to the Physical History of the British Isles*," 1882.

The earth-movements which, commencing towards the close of the Silurian period, resulted in a general uplift of the British area, and the ultimate filling of the great oceanic trough of early Palæozoic times, continued into Devonian times with increasing intensity. The change was, however, less pronounced in the south than in the north, with the result that in Devonshire, Cornwall and West Somerset, the marine Silurian strata are succeeded by marine Devonian strata, but the region to the north of the Bristol Channel was raised above the level of the sea, and became part of a great land mass that extended far to the north-east, across the site of the present North Sea to Scandinavia.

The geography of the time, as far as it can be interpreted from the evidence of the rocks, is indicated in *Fig.* 56.

The restoration of past geographical conditions.—This is a convenient point at which to refer to the means by which maps depicting the geographical conditions of past ages can be prepared. It is necessary to bear in mind that the British Isles as we know them came into existence in comparatively recent times. The land-mass which can be regarded as the basis of the present islands did not appear until toward the close of the Tertiary era, and the final separation of Great Britain from Europe took place after the arrival of primitive man. When, therefore, in connection with remote geological periods, like those under discussion, reference is made to any particular part of the British Isles, what is really meant is that part of the surface of the earth where the district in question is now situated.

Most rocks possess characters that indicate the conditions under which they were formed: in the case of those that accumulated as sediments, the fossils they contain indicate whether they were laid down in the sea or in a lake, and the nature of the rock indicates whether the material was laid down in muddy water or clear, or whether it accumulated along the shore (as beds of pebbles, now converted into the rock, conglomerate), in shallow water (as beds of sand, now converted into the rock sandstone), or where the water was sufficiently deep or far enough from land to be reached only by very fine sediment (giving rise to certain kinds of mud, now converted into clay or shale). Thus, by studying the distribution of the various kinds of rock formed at any particular period, it is often possible to indicate the position of the land and sea, and to trace, more or less accurately, the boundary between them at the time when the rocks were formed. It is on these lines that maps illustrating the geography of past times have been prepared by various workers, notably by Edward Hull [1] and A. J. Jukes-Browne [2].

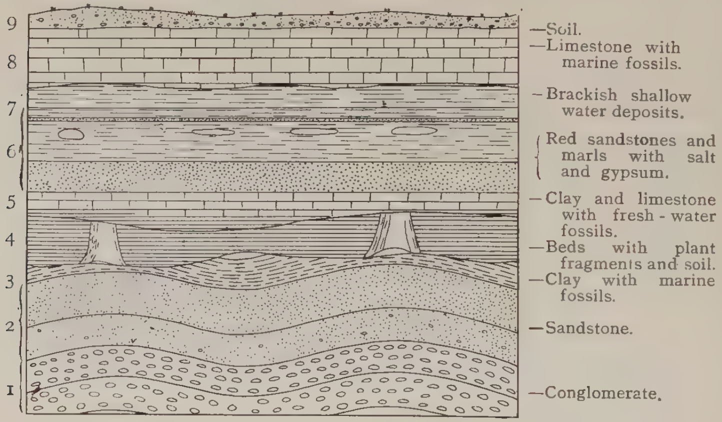
9
8
7
6
5
4
3
2
1
—Soil.
—Limestone with marine fossils.
—Brackish shallow water deposits.
Red sandstones and marls with salt and gypsum.
—Clay and limestone with fresh-water fossils.
—Beds with plant fragments and soil.
—Clay with marine fossils.
—Sandstone.
—Conglomerate.

FIG. 57.—DIAGRAM ILLUSTRATING THE INTERPRETATION OF THE EVIDENCE OF ROCKS CONCERNING PAST GEOLOGICAL CHANGES.

Not only do rocks indicate the conditions under which they were formed, and thus enable us to determine the distribution of land and sea in past ages, but, from a consideration of the way in which one kind of rock succeeds another in vertical sequence, they provide evidence as to the nature and extent of past changes.

The principle is illustrated in *Fig.* 57, which is an imaginary section of part of the earth's crust; in it, the sequence of events indicated by the rocks is as follows:—

The geological history of the district, as far as the time represented by the section is concerned, opens with the accumulation of pebbles along the sea shore (1); the land was slowly subsiding, and, in time, sand took the place of pebbles (2), but eventually there was comparatively deep water in which mud accumulated (3); earth movements then resulted in the folding, uplifting, and partial denudation of the strata, and dry land conditions prevailed for a time (4); slow local subsidence caused the formation of a freshwater lake (5), after which elevation and a change in climatic conditions gave rise to a desert (6). A further subsidence permitted the gradual return of the sea, which was at first shallow and muddy (7), but later became deeper and clear (8); finally, the region was again raised, the sea retreated, and dry land conditions now prevail (9).

The evidence, which is meagre and often obscure in relation to the earlier geological periods, becomes more abundant and more definite as the dawn of the human era is approached; and, therefore, the more recent the period the more successful will be the attempts to reconstruct the physical conditions. For earlier periods it is usually only the general trend of the coast line that can be determined, but for later periods the positions of bays and inlets, and of mountain ranges and valleys can be indicated with some degree of accuracy.

The geographical conditions of Devonian times.—Returning to our consideration of the geographical conditions of Devonian times, we find that the open sea, in which lived corals, crinoids, and many other typically marine animals, lay to the south, and in it were deposited muds (which are now slate), sandstones and limestones; to these rocks, Sedgwick and Murchison gave the name Devonian in 1839.

On the land mass to the north, there were estuaries or large lakes, in which there accumulated vast deposits of marl, sandstone, and conglomerate. The prevailing tint of the deposits is red, and they were named Old Red Sandstone in order to distinguish them from another red sandstone formation, the New Red Sandstone (Permian and Trias), which occurs much higher in the geological sequence, above the rocks of the Carboniferous system. Thus, the names Devonian and Old Red Sandstone designate different types of deposit formed at the same time—namely, between the end of the Silurian period and the commencement of the Carboniferous.

The fossils of the Old Red Sandstone are quite different from those in the typical Devonian rocks. No marine animals such as brachiopods or corals are represented, but an abundance of fish-like organisms and primitive fishes lived in the shifting estuaries of the large rivers that drained the northern continent, or in lakes that may from time to time have resulted from local expansions of those rivers.

During the Devonian period, dry land conditions were much more extensively developed than at any previous period since living things had appeared upon the earth : these conditions gave impetus to the development of plant life, but, except in the southern sea the conditions were not favourable to the formation of limestone, and calcareous rocks rarely occur in the Old Red Sandstone type of deposit, although the few that do occur are very interesting, and were once of considerable importance.

Limestones in the Old Red Sandstone.—The Old Red Sandstone consists, to a large extent, of sandstones, marls, and conglomerates, of which, in many regions, the prevailing tint is red. The red colour is due to the presence of a film of oxide of iron coating each particle of the rock; this suggests that the material accumulated in water, the circulation of which was restricted, and in a region where the oxidising influence of the atmosphere was greater than the reducing action of decaying vegetation. These conditions occur in arid regions, and it is believed that more or less desert-like conditions prevailed, during part of the Devonian period, over much of the land where the Old Red Sandstone accumulated. This conclusion is supported by the character of some of the fine-grained material in the marls, which is strongly suggestive of wind-blown dust.

The rock succession of the Old Red Sandstone varies from place to place; that in South Wales, for example, is very different from that in the north of Scotland, but since it is only in the south that limestones are developed sufficiently to have been of economic importance, the Scottish Old Red Sandstone does not need detailed discussion here. In the extreme north of Scotland, the Caithness Flags, which are mostly flaggy sandstones rich in fossil fishes, contain some thin beds of dark bituminous limestone.

In South Wales and the border counties the Old Red Sandstone includes the following sub-divisions :—

(*c*) Sandstones and conglomerates; maximum thickness 500 feet.

(*b*) "Brownstone" Series; flaggy sandstones and marls; maximum thickness 1,500 feet.

(*a*) "Cornstone" Series; marls and sandstones with limestones (cornstones); maximum thickness 4,000 feet.

The calcareous rocks are almost confined to the lower division, which consists principally of hard reddish-purple and often sandy marls, and yields a soil particularly favourable to the growth of corn, hence the name "Cornstone."

The limestones occur either in definite lenticular beds, or as isolated nodules or beds of nodules; they are light in colour, being usually pale red or pale green. Their origin is doubtful; they are devoid of fossils, except perhaps for obscure traces of plant structures, and they cannot have been ordinary deposits of shell or coral debris. They are fine in grain and amorphous in structure, and it is very likely that they represent calcium carbonate, precipitated partly as a result of the evaporation of the water in which it was dissolved, and partly by the action of calcareous algæ.

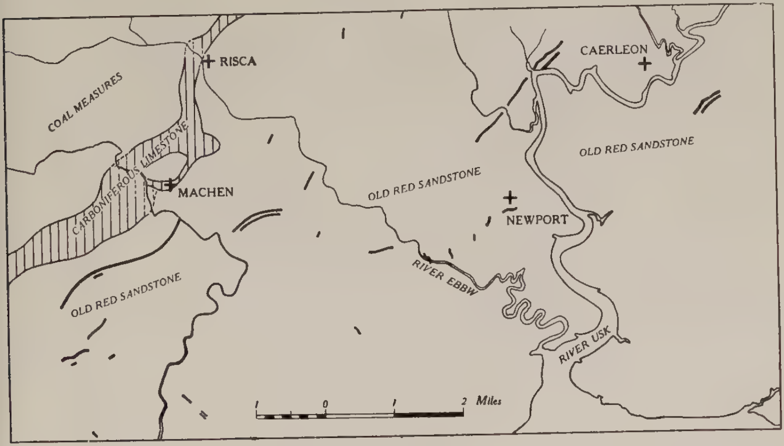

FIG. 58.—SKETCH MAP OF PART OF THE OLD RED SANDSTONE REGION OF MONMOUTHSHIRE,

showing the distribution of thin beds of limestone (cornstones) which are represented by black lines. The small discontinuous limestone outcrops contrast strongly with that of the Carboniferous Limestone which is a massive limestone formation.

The lenticular beds may have a thickness up to five or six feet; some are very local in their distribution, while others extend for several miles, and although impersistent, the beds tend to reappear elsewhere at the same horizon (*Fig.* 58); in this respect they are like the marine limestones in the Bala division of the Ordovician rocks. The massive limestone beds sometimes pass into marls crowded with detached nodules, and locally there are what appear to be conglomerates of slightly waterworn cornstone nodules, the occurrence of which is probably due to the fact that, soon after its formation, a nodule-bearing marl was locally disturbed by currents that washed away the marl, and left the nodules behind [3].

The passage of the beds of limestone into layers of isolated nodules favours the suggestion that the material was deposited chemically or by algal activity; in some places the amount of lime deposited was sufficient to form a continuous bed, but as a rule, it was only enough to form isolated masses in the soft sediment that was accumulating.

The presence of so much calcareous material may be due to the fact that limestones of Ordovician and Silurian age were undergoing denudation at the time. It is possible that the calcium carbonate was not all carried in solution; some of it may have been laid down directly as calcareous mud, for the waters of the Cam, near Cambridge, have been found to contain solid calcareous matter, such as foraminifera and other fragments derived from the Chalk [4].

The " cornstone " limestones are found, among other places, near Hereford, between Monmouth and Abergavenny, near Usk, between Newport and Cardiff, and near Ferryside and Llanstephan in Carmarthenshire; they are practically absent from the Brecknock Beacons and the Carmarthenshire Van country, where the Cornstone Marl Series is not typically developed and the " Brownstone Series " is well displayed.

Wherever they occur in sufficient quantity the cornstones have been worked for lime-burning and road-metalling, and in days when transport was difficult they must have been of considerable importance in the marl-country of the Welsh borderlands, where they were not only the sole local source of lime, but the only material hard enough to be used for repairing roads. In many instances the available limestone has been practically worked out, but old kilns in the heart of the " Old Red " country tell of its former importance.

The marine Devonian rocks.—In South Devon and Cornwall the Devonian rocks are normal marine deposits, and they consist of alternations of shale (often now in the condition of slate) and sandstone, with, locally, some important beds of limestone. The limestones are more abundant in the south, between Torquay and Plymouth, than in North Devon and the adjacent part of West Somerset; this, together with the fact that in North Devon the strata include some red sandstones similar to those of the Old Red Sandstone, suggests that marine conditions were continuous in the south, although the shore of the land on which the Old Red Sandstone accumulated occasionally moved as far south as the site of the present Forest of Exmoor.

The Devonian deposits in the south-west of Ireland bear a greater resemblance to those of North Devon than to those of South Dévon or those of the Old Red Sandstone regions.

The marine life of the Devonian period was more or less intermediate in character between that of Silurian times and that of the Carboniferous period. In the Lower Devonian rocks many important Silurian types are found to die out, and in the Middle and Upper Devonian, members of the Carboniferous fauna begin to appear. Graptolites, so important in the lower Palæozoic rocks did not survive into the period; trilobites were on the wane, but corals (*Figs.* 59 and 21), stromatoporoids* (*Fig.*

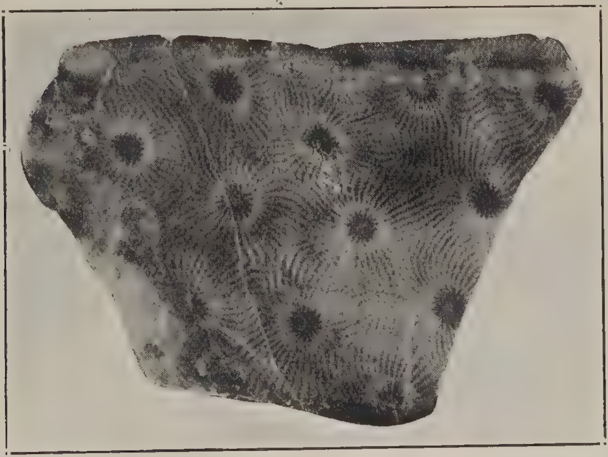

FIG. 59.—A DEVONIAN CORAL.

Smithia pengellyi (M. Edwards) from the Middle Devonian Limestone of Devonshire; natural size.

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* The Stromatoporoids constitute a group of the Hydrozoa—the class to which graptolites belonged. Unlike the graptolites, however, they secreted massive calcareous skeletons with a kind of netted structure, in which each polyp had its own pore or tube. They first appeared in the Ordovician period, increased in importance until Devonian times, and then died out.

60), brachiopods, and molluscs had increased enormously in variety and abundance, and the two first named are the most conspicuous fossils in the calcareous rocks. Limestones were formed wherever conditions favoured the growth of animals, such as those mentioned, in water that was more or less free from land-derived sediment.

Limestones in the marine Devonian strata.—In South Devon and Cornwall the Devonian rocks have been divided into three groups—the Lower Devonian Rocks are mostly slates and grits; the Middle Devonian group includes slates and volcanic ashes with (locally) an enormous development of limestone; and the Upper Devonian rocks consist mostly of shales and slates, but contain some massive grey limestones. The passage from the limestone to the shale is not usually sharp, and there is every gradation between calcareous slates and the massive limestones.

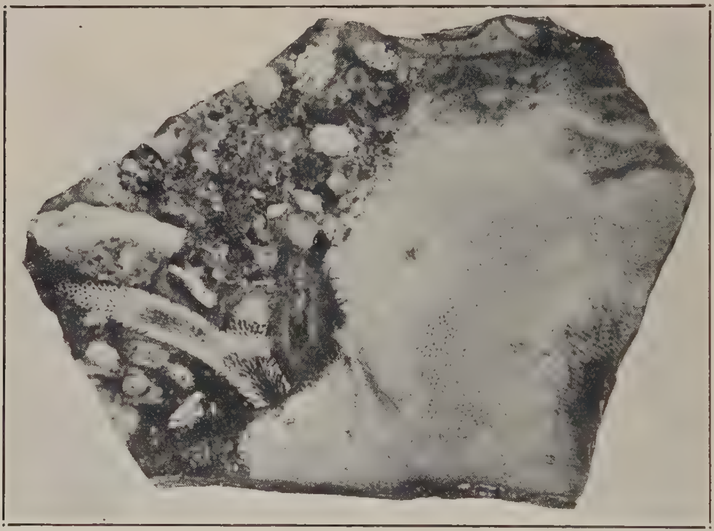

FIG. 60.—LIMESTONE CONTAINING STROMATOPOROID SKELETONS,

from the Middle Devonian rocks of Devonshire; slightly reduced in size.

It is in the middle division that most of the economically important limestones are found, and they occur at more than one horizon or geological level in the series. The lower limestones are generally dark grey or nearly black well-bedded rocks; they are typically developed around Dartington, Ashburton, Dartmouth, and Torquay, and often consist largely of fragments of crinoids (*Fig.* 229), but layers crowded with coral remains occur at intervals.

The higher limestones are lighter in colour, showing shades of grey, white, pink, and red; they are often veined or mottled, and some varieties make beautiful ornamental "marble." They are mostly massive rocks with little or no evidence of stratification, and are typically developed around Plymouth and around Torquay, where they are over 200 feet in thickness; corals and stromatoporoids are the commonest fossils.

The pink and red tints are due to the infiltration of iron-bearing waters from the New Red Sandstone strata, which formerly stretched much farther west than the edge of their present outcrop (which extends from Exeter to Paignton) but have been denuded in comparatively recent geological times.

Near Plymouth, West Ogwell, and other places, the massive limestones of the Middle Devonian pass up into limestones of Upper Devonian age—the latter include red or pink coloured varieties, some of which contain corals in abundance, while in others, goniatites occur. (Goniatites are members of the molluscan group, cephalopoda, see page 432, and they were the ancestors of the ammonites.)

Examination under the microscope shows that, on the whole, the limestones consist of fragments of crinoids, and corals; the small shells of the foraminifera which are so abundant in the Carboniferous Limestone are almost absent, and there is no development of oolitic structure. Some beds contain recognisable fossils, either broken or entire, but others appear to consist of fine grained material derived from calcareous structures so completely disintegrated as to have given rise to a kind of calcareous mud.

The rocks show much variation in mechanical condition; some are very little altered, but others (for example, those at Babbacombe) are completely recrystallised. In some places they show signs of having been much affected by the pressure which produced cleavage in the rocks of the district that are now slate, but this feature is more noticeable in the limestones of North Devon than in those of the south. The phenomena of dolomitisation are well displayed, as for example at Lummaton, near Torquay, and there is every gradation between limestones that are unaltered and those that are completely dolomitised [5, 6].

On account of the abundance of corals in some of the limestones it has often been stated that they originated as coral reefs growing in the Devonian seas, but this is far from being the case. A coral reef results from the long continued growth of corals, usually on a sinking sea floor; blocks of coral dislodged by the waves may be piled up against the reef, and owing to the fact that the angle of rest is steeper in water than on land, the seaward slope of a coral-reef mass is usually very steep, sometimes as much as 60 or 70 degrees. A limestone mass formed from such a reef would be somewhat irregular in outline and have sharply defined limits, but the coral-bearing limestones of Devonshire are really beds of coral debris, indicating times when corals were temporarily abundant—when they grew, died, fell to pieces, and were distributed over the sea floor.

The coral skeleton is cellular in structure and is very porous, but after the death of the animal, the pores in the skeleton, the cavities occupied by the individual polyps, and the spaces between the separate colonies, all become filled, partly with calcareous sand and mud consisting of finely divided coral, and partly with material deposited by the activities of calcareous algæ, resulting in the formation of a compact mass that may subsequently give rise to dense limestone. During this process of consolidation and cementation the structure of the fossils may have been, to some extent, obscured by partial solution, or it may have been preserved with remarkable thoroughness—every plate and septum in the skeleton being sharply defined on polished surfaces (see *Figs.* 21 and 59).

The rocks have been used as ornamental marbles (especially for internal decoration), as building stones and for road-making. They have also been used for lime-burning, but, as in many other areas, to a less extent now than formerly. For building purposes blocks of moderate size are easily obtained and are used either with or without dressing. The stone usually wears well, but like other limestones it is liable to deteriorate owing to the action of boring organisms if used in structures such as sea-walls and breakwaters, where it is more or less continuously covered by sea water (*Fig.* 61). Limestone from Oreston, near Plymouth, was used in making the breakwater at the latter place, but between high and low water marks it soon was so perforated by the mollusc *Pholas dactylus* (see page 34), that the blocks had to be replaced by granite.

Some of the quarries in the massive ill-stratified limestones have yielded blocks of very great size; for example, from Ipplepen quarries between Newton Abbot and Totnes, where one of the most beautiful limestone-marbles occur, polished monolithic columns over 12 feet high were obtained for the National Provincial Bank, Bishopsgate, London. Owing to the harmony of colour that prevails among the rocks, it has been the practice to use, in the same scheme, varieties from different quarries.

There are many isolated outcrops of limestone in South Devon [7-12]; some are very small, while others cover areas up to three or four square miles (*Fig.* 62). In the west a long narrow strip extends from Devonport to Plymouth, and another occurs at Yealmpton. The rock abounds in fossils, and the texture is generally crystalline; the colour ranges from red to brown and from black to white. It has been used for building walls, and as an ordinary building stone, while the pale red varieties have furnished ornamental stone, mostly for monumental work and church decoration. At one time the limestone was carried in barges up the estuaries, and burnt into lime for agricultural use; this accounts for the local abundance of old kilns far away from the limestone outcrops; lime for building is still prepared. Many years ago, Sir H. T. de la Beche (*Fig.* 63), when Director of

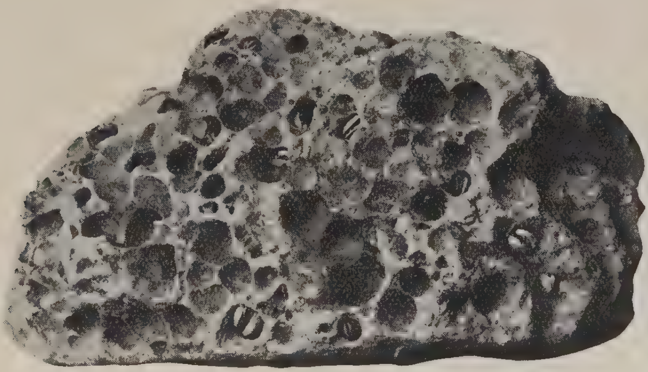

FIG. 61.—LIMESTONE WITH HOLES MADE AND OCCUPIED BY THE MOLLUSC, *Saxicava.*

Certain bivalved molluscs, especially *Saxicava* and *Pholas,* live in holes that they bore for themselves in limestone and other soft rocks, and by thus weakening the surface layers of the stone, facilitate its destruction by mechanical means; photograph one-half natural diameter.

the Geological Survey, drew attention to the durability and other desirable characters of the limestone at Yealmpton [13].

The eastern outcrops extend intermittently from near Chudleigh in the north, to Brixham in the south. The dark limestones at Chudleigh are used for roadstones. From Buckfastleigh, a narrow broken outcrop extends by way of Ashburton in a north-easterly direction for about 6 miles. The rock is similar to that of the main outcrop near Newton Abbot; most of it is dark grey, often veined with calcite or brecciated, and it is worked for lime, marble, and building stone; marble capable of receiving a good polish is also obtained from a thin reddish band full of fossils.

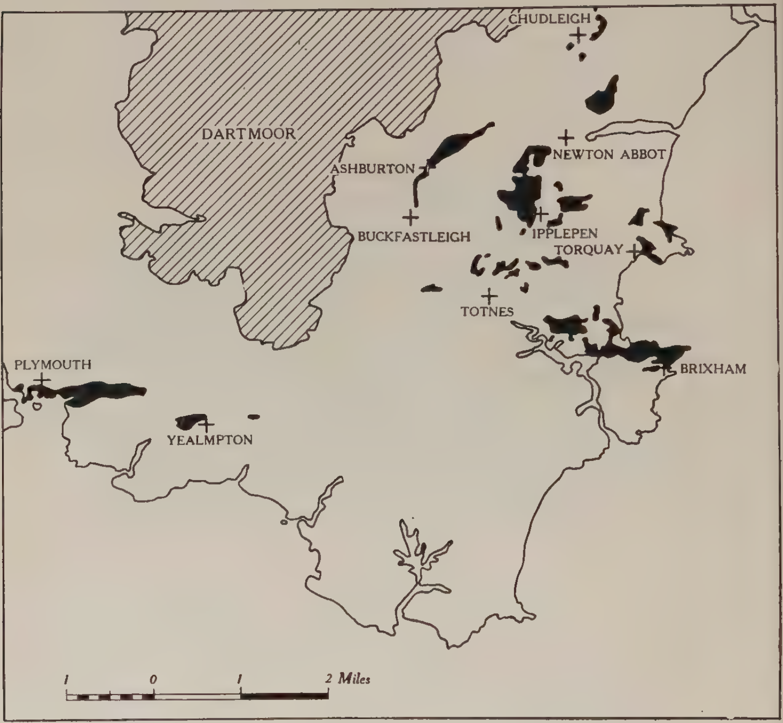
CHUDLEIGH
DARTMOOR
NEWTON ABBOT
ASHBURTON
BUCKFASTLEIGH
IPPLEPEN
TORQUAY
TOTNES
PLYMOUTH
BRIXHAM
YEALMPTON
1
0
1
2 Miles

FIG. 62.—The distribution of limestone in South Devonshire.

The limestones which occur in rocks of Middle Devonian age are represented by dense black, and the oblique lines indicate the outcrop of the Dartmoor granite.

A large limestone mass extends southwards from Newton Abbot, by way of West Ogwell to Ipplepen. Here the rock includes purplish grey, and grey veined varieties. At Kingskerswell there is a pink variety crowded with the shells of the straight cephalopod *Orthoceras* (*Fig.* 64), which, being lighter in colour than the matrix, give the rock a striking appearance.

At the Ogwell Quarries, near Newton Abbot, red and grey varieties are obtained, while at Bradley Woods, there is a highly fossiliferous rock containing in abundance the coral *Pachypora cervicornis* (*Fig.* 21); this rock was at one time in great demand for table tops and similar objects.

The purplish-grey marbles of Ipplepen have already been mentioned. Further south there are limestone masses at Babbacombe and Torquay (where the rocks are much folded and affected by faults), and others between Berry Pomeroy and Brixham; the more massive varieties at Torquay and Brixham have been extensively quarried for building stones, while black "marble" with veins of white calcite, has been obtained at Berry Pomeroy.

At Lummaton some of the rock consists principally of broken shells, and it must have originated as a shell-bank in shallow water that was exposed to the action of strong tides [14]. There are also dove coloured crystalline coralliferous limestones, some of which are highly dolomitised.

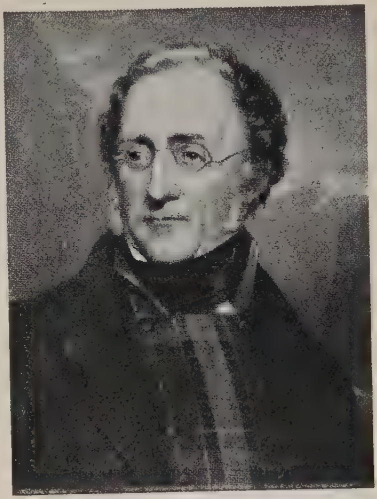

FIG. 63.—SIR H. T. DE LA BECHE (1796-1855).

First Director-General of the Geological Survey. (Reproduced by permission of the Council of the Geological Society.)

As is usually the case with extensive limestone masses, fissures —even large caves—have been formed in the Devonian limestone as a result of the solvent action of water charged with carbon dioxide, and some of the most interesting caves that have yielded the remains of primitive man and the animals that were contemporary with him occur in Devonshire. Among these are Kent's

Cavern, near Torquay, while a cave at Oreston, discovered in 1816, was the first bone-bearing cave to be scientifically investigated in this country; it yielded, among other things, the bones of an extinct species of rhinoceros [15-18].

In North Devon and West Somerset the Devonian rocks are of marine origin, and they consist chiefly of grey slates and sandstones, with thin lenticular earthy limestones in the Pilton Beds near the top, and also in the Ilfracombe Beds near the middle of the Formation.

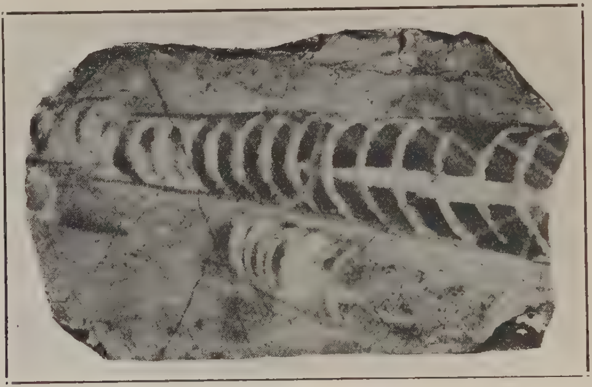

FIG. 64.—A DEVONIAN CEPHALOPOD.

Orthoceras, from the Middle Devonian Limestone of Teignmouth; about two-thirds natural size.

The marine Devonian limestones are now of more economic importance than any that occur among strata of greater age in this country. In a recent year, the output from Devonshire, where most of the outcrops occur, was over 270,000 tons, mainly from the Plymouth, Newton Abbot, and Ashburton masses. Most of this was obtained for road-making and building purposes, but greater use could be made of the ornamental varieties, because much of the domestic "marble" can withstand the British atmosphere better than many of the foreign crystalline marbles that are imported into this country.

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CHAPTER VII.

LIMESTONE IN THE CARBONIFEROUS SYSTEM OF ROCKS.

> ". . . that important assemblage of calcareous strata . . . which has been often described by the name of mountain limestone, from its usually forming considerable hills; of metalliferous limestone, from its mineral riches; and of entrochal or encrinal limestone, from its organic remains. We prefer to all these that of *carboniferous limestone,* derived from its association in the coal districts, as expressing a character more constant and more peculiar than any of the former."
>
> W. D. CONYBEARE, 1822 [28].

In our consideration of the rocks of this country in the order of their formation, the Carboniferous System is the first to be encountered in which limestone plays an important part, for over most of the British area the lower part of the System is made up almost entirely of limestone—the Carboniferous Limestone—and in discussing the calcareous rocks of the Carboniferous System we are not, as hitherto, dealing with a few limestones scattered amidst a wide expanse and a vast thickness of sandy and clayey sediments, but with a limestone formation covering, in the area with which we are concerned, many hundreds of square miles, and of which the maximum thickness is about 3,000 feet (*Fig.* 65).

The Geographical conditions of Carboniferous times.—The movements in the earth's crust that resulted in the arid mountainous country of Old Red Sandstone times eventually grew less intense, and there commenced a period of comparative tranquillity during which the British area as a whole began to sink; the sea gradually encroached upon it, until, except for certain tracts of higher ground which remained as islands, England, Wales, Ireland, and the south of Scotland were covered by the sea. The waters of the sea, except in the extreme north and in the extreme south, were remarkably free from land-derived sediment, because the surrounding lands were not raised much above sea level, so that the rivers, flowing down gentle slopes, could do very little in the way of excavation and transport.

The earth-movements of Devonian times had been accompanied by volcanic activity: this, like the crustal disturbances from which it resulted, died out gradually, and there were occasional volcanic outbursts during the earlier part of the new marine period. The activity was most intense in the south of Scotland, but minor eruptions occurred in Derbyshire, and a small volcano arose on the sea floor, pouring out lava and ejecting ashes, near Weston-super-Mare.

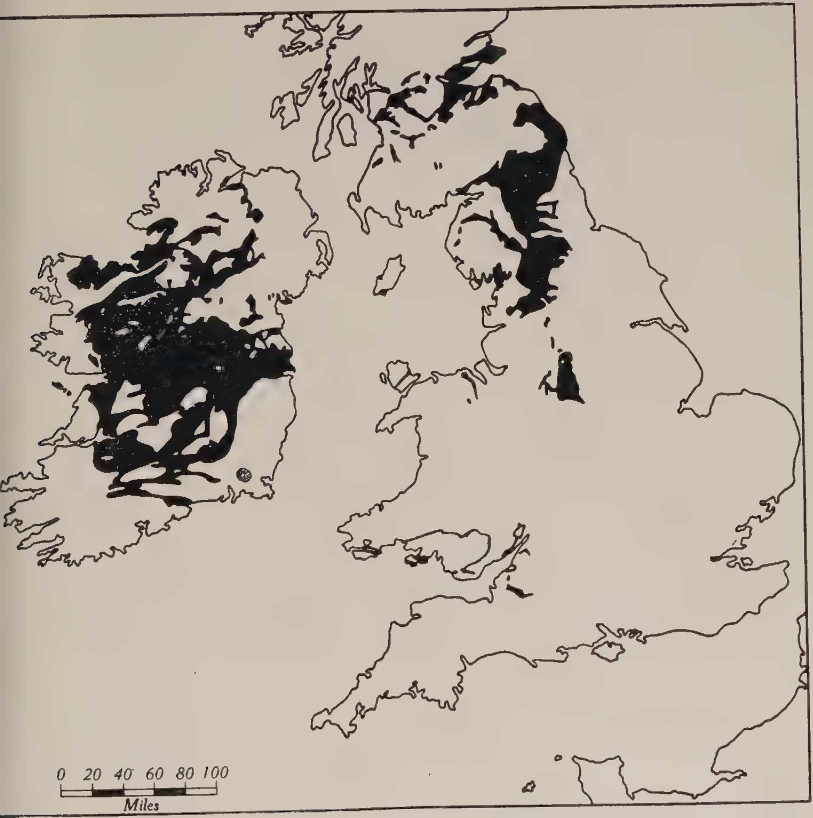

FIG. 65.—THE DISTRIBUTION OF THE CARBONIFEROUS LIMESTONE IN THE BRITISH ISLES.

The outcrops of the Carboniferous Limestone are represented by black.

The boundaries of the Carboniferous Limestone Sea at the period of its maximum extent are indicated in *Fig.* 66, from which it will be seen that in the centre of the more or less enclosed sea there was an island, to which Jukes-Browne gave the name *St. George's Land,* extending from the Midlands of England across Wales and the Irish Sea. This was at first of considerable size—

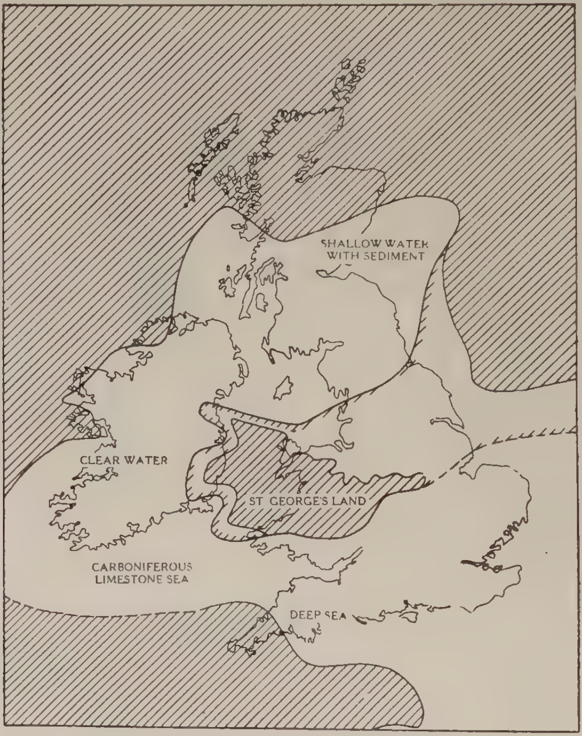

FIG. 66.—MAP ILLUSTRATING THE GEOGRAPHY OF THE BRITISH AREA DURING CARBONIFEROUS LIMESTONE TIMES.

Lines indicating the probable distribution of land and sea at the time of the formation of the Carboniferous Limestone are superimposed upon a map of the British Isles. Towards the end of the period, elevation appears to have converted "St. George's Land" into a peninsula connected with the mainland on the east. During Carboniferous Limestone times the Southern Uplands of Scotland existed as an island, which is not indicated on the map (after A. J. Jukes-Browne).

in all probability it originated as a peninsula—but as the downward movement continued, it was gradually submerged until it assumed the form indicated in the map.

Like most other maps depicting the geography of past ages, that in *Fig.* 66 can only be regarded as approximate, but as the extent of our knowledge increases greater accuracy will be attained. For example, the map here given is based largely upon that prepared by Jukes-Browne many years ago, and with which all students of the geography of the past are familiar, but in a recently published paper Dr. E. Greenly has demonstrated that the site of the Snowdonian mountain mass of Caernarvonshire was also beneath the sea during part at least of Carboniferous Limestone times, thus bringing the middle region of the northern shore of St. George's Land further to the south than Jukes-Browne supposed it to be [1].

As the sea encroached upon the land, pebble beds were sometimes formed along the shores, and in many places the lowest beds of the Carboniferous Limestone Formation consist largely of conglomerates and sandstones; they are seen, for example, in Flintshire, near Llangollen, along the Menai Straits, and also in North Lancashire and Westmorland [1a].

The subsidence was, at first, greater to the south of St. George's Land than north of it, and the deposition of limestone began earlier in the former region—the South-western Province, as it is called in the literature of Carboniferous Limestone geology — than in the Midlands and in the North of England. The encroachment of the sea was gradual, so that there is, in most places where there is no development of a basal conglomerate, an almost imperceptible passage from the Old Red Sandstone to the Carboniferous Limestone; in such cases the lower part of the latter consists, not of comparatively pure shelly limestones such as constitute a large part of the Formation, but of thin (and often impure) limestones, alternating with shales, known collectively in the South-western Province, as the Lower Limestone Shales.

The climate, like that of the preceding Devonian period, was dry, and St. George's Land must have stood very little above sea level, with the result that the few rivers flowing from it carried but little sediment into the sea. The rivers that entered, from the south, the region of deep sea over the site of Devonshire and Cornwall, brought down mud that gave rise to the black shaly deposits, which in that district take the place of the Carboniferous Limestone.

Since the maximum thickness of the Carboniferous Limestone is over 3,000 feet, and it was deposited upon a floor that at the close of Devonian times was either near or above sea level, the whole region must have been sinking, or the basin would soon have filled up. The subsidence was, however, neither continuous, nor uniform in rate, for at various levels in the limestone there is evidence of the occurrence of very shallow water conditions, and, in places, of the actual raising of the surface of the newly formed deposit above sea level for a short time [2, 3, 4].

One instance of temporary emergence may be cited in illustration of the way in which the evidence for presuming the occurrence of such changes is interpreted. On the north-eastern coast of Anglesey, at Dwlban Point, there are vertical pipe-like masses of sandstone descending into the Carboniferous Limestone from a bed of sandstone that occurs within the formation. The nature of the junction of the two rocks indicates that the limestone upon which the sandstone was deposited had been exposed to atmospheric weathering. An uneven surface was produced, joints were widened, and fissures, such as those to be seen in almost any exposed mass of Carboniferous Limestone, were formed (*Fig.* 67). When the area again sank beneath the water, sand was deposited, descending into and filling the fissures, before the conditions were again favourable to the accumulation of limestone. This took place *during* Carboniferous Limestone

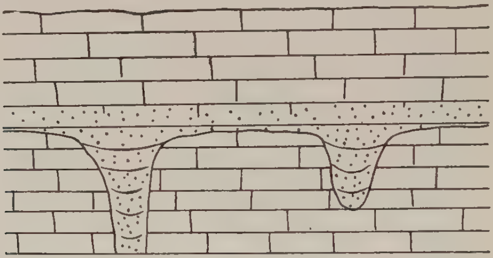

FIG. 67.—"PIPES" IN THE CARBONIFEROUS LIMESTONE.

Diagram (after E. Greenly) illustrating the formation of sandstone pipes within the Carboniferous Limestone of Anglesey, owing to temporary upheaval which exposed the surface of the limestone to sub-aerial denudation, followed by subsidence and a resumption of limestone-forming conditions.

times, because the sandstone with which the material in the pipes is continuous, is only a thin bed in the Limestone series [5].*

St. George's Land was never completely covered during Carboniferous Limestone times (*Fig.* 8), but as the subsidence proceeded, the sea passed around its western extremity and entered the northern area of deposition; since, however, land conditions continued in the north after the sea had invaded the South-western Province, the lowest beds of the Carboniferous Limestone in the Northern region are not so old as the lowest beds in the South-western Province. As was the case in the south, St. George's Land furnished very little sediment to the northern sea basin, for in Derbyshire, a few miles to the north,

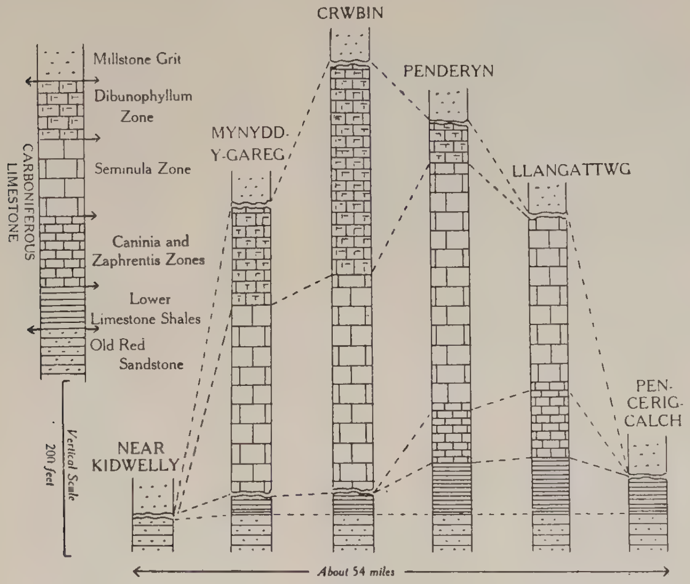
CRWBIN
Millstone Grit
Dibunophyllum Zone
PENDERYN
MYNYDD-Y-GAREG
CARBONIFEROUS LIMESTONE
Seminula Zone
LLANGATTWG
Caninia and Zaphrentis Zones
Lower Limestone Shales
Old Red Sandstone
PEN-CERIG-CALCH
Vertical Scale
200 feet
NEAR KIDWELLY
About 54 miles

FIG. 68.—SECTIONS ILLUSTRATING THE VARIATION IN THICKNESS AND LITHOLOGICAL CHARACTERS EXHIBITED BY THE CARBONIFEROUS LIMESTONE ALONG THE NORTHERN EDGE OF THE SOUTH WALES COALFIELD.

Careful study, in the light of the fossils present in the rock, shows that when traced from one place to another, certain "zones" of the limestone maintain a fairly constant thickness, while others are very variable and may even be local in their distribution; after T. N. George and T. Robertson [11a].

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* See Additional Note, page 446.

pure limestone was deposited to a very considerable thickness, but when traced into Leicestershire—that is towards the shore of the island—the limestone thins out rapidly until it becomes only about 40 feet thick, and includes thin sandy beds, representing material discharged into the sea by a few small streams.

Before the end of Carboniferous Limestone times, the sea had covered practically the whole of England, Ireland, and the south of Scotland. A good deal of sediment was brought down by the rivers flowing from the northern continent, and in Scotland and Northumberland there are indications that the subsidence was not only slow, but intermittent, for in that region the Lower Carboniferous rocks consist of alternations of shales and sandstones to which limestones are subordinate. The latter were formed during periods of subsidence, and the former when there was either elevation or a cessation of subsidence long enough for the sea basin to have been locally choked with sediment. At times, swampy mud flats, a little above sea level, were formed and maintained long enough for forests to grow upon them, providing material that afterwards became coal seams. These were the forerunners of the much more extensive forests that existed during later Carboniferous times, and account for the fact that in the south of Scotland and Northumberland, coal seams occur in the lower part of the Carboniferous Formation, which further south, consists entirely of marine rocks, and principally of limestone.

Taking the region as a whole, the continual rain upon the sea floor of the shells and skeletons of the creatures that were living in the water, served to keep it at a fairly uniform depth for a long period of time, except, of course, for the local interruptions to which reference has already been made. Eventually, however, the downward movement ceased, and for a time it was replaced by one of rather rapid upheaval. The slopes down which flowed the rivers of the neighbouring lands became steeper, and the streams were more active in wearing away the rocks.

They were able to carry pebbles and coarse sand along with them, and sediments of that type began to take the place of shelly calcareous accumulations. This new series of rocks is known as the Millstone Grit, because in the north it contains coarse gritty rocks, that were at one time in great demand for making mill-stones, although in many places it consists of sandstones and shales.

The upward movement brought to an end the first great limestone forming epoch represented among the rocks of this country, and the foregoing description of the geographical conditions and changes during Carboniferous Limestone times will assist in explaining the reason for the existence of so many varieties of limestone in the Formation, and the great differences in the vertical succession of the rocks in the various regions where they are exposed.

Fig. 68 illustrates the lateral variations seen in the limestone in a region where slight earth-movements were in progress during the early part of Carboniferous times.

The fossils of the Carboniferous Limestone. — Before describing the distribution of the limestone and its uses, it will be convenient to refer to the fossils found in it, and to the manner in which they have been used to subdivide the rock into "zones."

The small-shelled foraminifera are very abundant at certain horizons, and often contribute largely to the bulk of the rock (see *Figs.* 27 and 228). Corals, too, are very abundant in some beds (*Figs.* 73 and 78), but as in the case of the Devonian corals, they do not usually represent coral reefs formed near to the shore, but are scattered throughout the rock over large areas. Crinoids or "sea-lilies" (which had very substantial supporting-structures of calcium carbonate (*Figs.* 22 and 23), bryozoa,

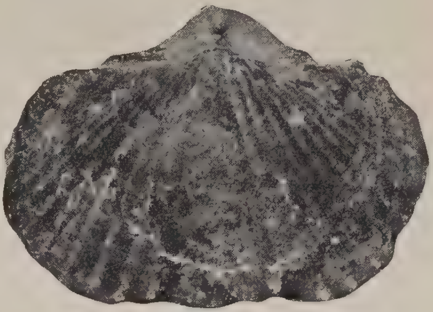

FIG. 69.—A FOSSIL BRACHIOPOD.

Spirifer pinguis (Sowerby) from the Carboniferous Limestone of Lancashire; about three-fourths natural size.

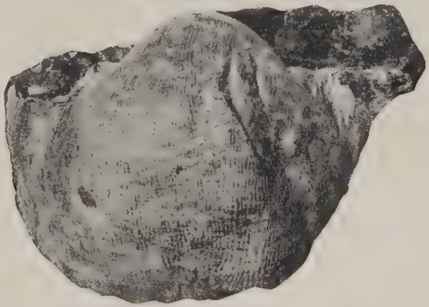

FIG. 70.—A FOSSIL BRACHIOPOD.

Productus giganteus (Martin) from the Carboniferous Limestone of Llangollen, North Wales; about one-third natural size.

brachiopods (*Figs.* 69 and 70), and molluscs are all varied in kind and numerous in individuals. Sometimes the bulk of the rock may be composed of nearly complete shells of one kind of shell-bearing animal, or of one kind of coral, or of the fragments of crinoids, but as a rule the fossil contents of the limestone are mixed. Trilobites were very rare, but marine fishes were more numerous than hitherto, and although for the most part they had skeletons of cartilage and not of bone, the strong crushing teeth with which some of them were provided are occasionally abundant.

Just as each of the geological systems is characterised by a set of fossils peculiar to it, so various levels within a System can often be recognised by means of the fossils they contain. Working on the extensive exposures along the banks of the Avon at Bristol, the late Dr. Arthur Vaughan showed that in the Carboniferous Limestone there are five well-defined stages or " zones " in vertical succession, each with a more or less distinctive assemblage of fossils [6].

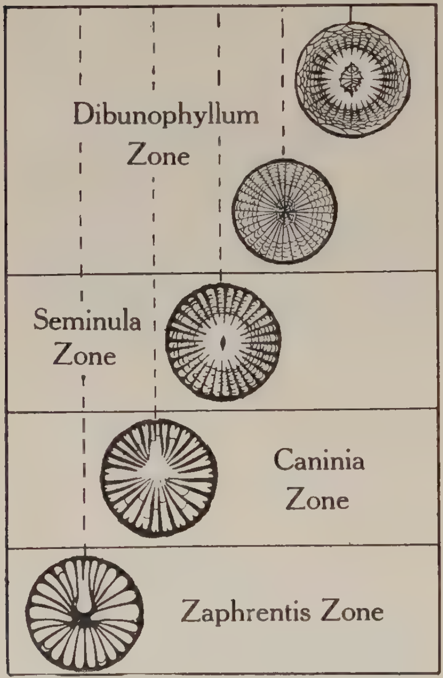

FIG. 71.—SOME CORALS CHARACTERISTIC OF THE CARBONIFEROUS LIMESTONE.

Sections, somewhat diagrammatic, of the corals (commencing with the lowest) *Zaphrentis, Caninia, Lithostrotion, Dibunophyllum,* and *Lonsdaleia.* These forms are characteristic of or make their first appearance in the Zone with which they are associated in the diagram: for example: *Lithostrotion* first appears in the *Seminula* Zone and is found also in the overlying deposits, but not in those below. The sections are not to scale, that of *Zaphrentis* being somewhat enlarged, and those of *Caninia* and *Dibunophyllum* considerably reduced: after Lang [49] and Neaverson [50].

Each of the zones was named after one of the fossils which, if not peculiar to it, was especially characteristic of it, and subsequent work has shown that on broad lines the same sequence of fossil-zones holds good in other areas, so that the limestone of one district can be compared or correlated with that of another, unless subsequent alteration such as dolomitisation has resulted in the obliteration of the fossils [1, 2, 3, 7-11].

The vertical sequence of the five main fossil zones is as follows:—

Dibunophyllum Zone—*Dibunophyllum* is a stout, more or less cylindrical simple coral; *Fig.* 71.

Seminula Zone—the zone fossil is a rounded, smooth shelled brachiopod.

Syringothyris Zone or Caninia Zone — *Syringothyris* is a brachiopod in which the shell of one valve is more or less conical (*Fig.* 72), and *Caninia* is a simple cylindrical coral.

Zaphrentis Zone — *Zaphrentis* is a small, simple, conical coral; *Fig.* 73.

Cleistopora Zone—*Cleistopora* is a compound coral, the surface of which has some resemblance to a fragment of honeycomb; see Additional Note, page 446.

The Distribution of the Carboniferous Limestone.—In dealing commercially with the Carboniferous Limestone it is necessary to bear in mind that the blue tint used on geological maps to indicate the outcrops of the rock is intended to represent the strata which occur between the Devonian rocks below, and the Millstone Grit above, and that there are many different kinds of limestone included under the one name: some of the varieties are of economic importance, and others are practically useless. The characters of the rocks of various areas have been described in papers published in recent years [12, 13], and the names of the fossil-zones have been introduced here because the published accounts can be more readily appreciated by one familiar with those names. In the South-western Province, for example, the limestones of the *Cleistopora* Zone are mostly impure, thinly bedded, and associated with shale, and those of the *Syringothyris* Zone are white or pale coloured oolites, while the pure limestones of Derbyshire which are so suitable for lime-burning are of *Dibunophyllum* age.

Although once continuous over most of England, Wales, and Ireland, the Carboniferous Limestone has been removed by denudation in some places, and in others it is covered by newer strata, so that it now appears in a number of separate outcrops that can, with convenience, be considered separately.

The South-western Province.—The Carboniferous Limestone of this region emerges from beneath a covering of newer strata to form the Mendip Hills; it underlies the coalfields of Bristol and the Forest of Dean, and in South Wales it appears as a band of variable width encircling the outcrop of the coal-bearing strata except where missing as a result of faulting, or covered by newer strata or by the sea, as in Swansea Bay and Carmarthen Bay (*Fig.* 39); it is also well displayed in the cliffs of South Pembroke-

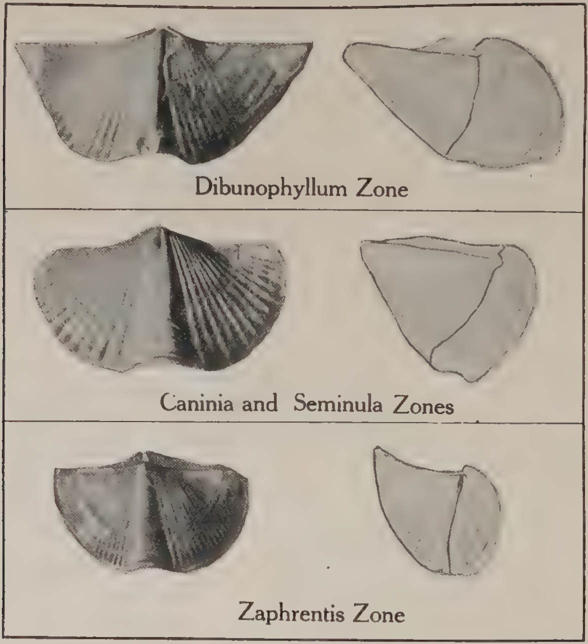

FIG. 72.—*Syringothyris*, A BRACHIOPOD CHARACTERISTIC OF THE CARBONIFEROUS LIMESTONE.

The illustrations show how the members of one genus of brachiopoda—*Syringothyris*—exhibit a progressive change in shape and size as they are traced from lower to higher beds in the Carboniferous Limestone; "front" views on the left, "side" views on the right.

The forms illustrated are those characteristic of the Zones indicated, and are reproduced about two-thirds natural size. The changes in external appearance are also accompanied by changes in internal structure [32].

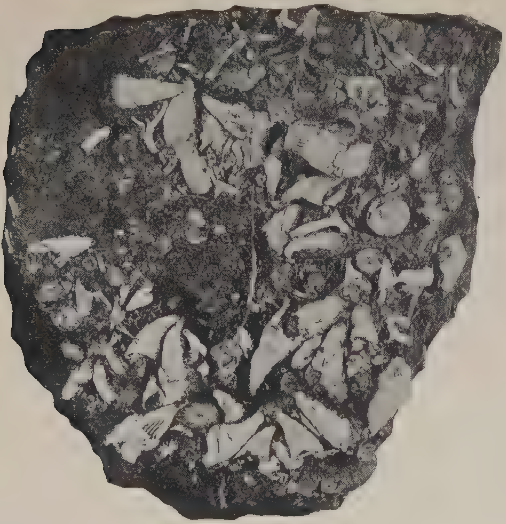

FIG. 73.—LIMESTONE WITH FOSSIL CORALS.

Zaphrentis, in the Carboniferous Limestone of Barry, Glamorgan; about two-thirds natural size.

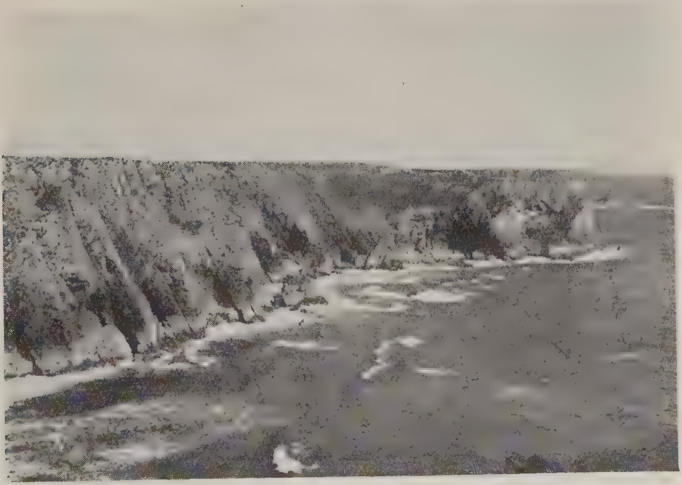

FIG. 74.—CLIFFS OF CARBONIFEROUS LIMESTONE, NEAR BOSHERSTON, PEMBROKESHIRE.

The rocks are steeply inclined, and the nearly flat surface of the land is due to levelling by wave action in Pliocene times. (*Photo F.J.N.*)

shire; *Fig.* 74. The rocks are mainly calcareous, and are all of shallow water origin; at several levels there are limestones of a peculiar type, associated with shales containing the bivalved shell, *Modiola,* and which must have been laid down in shallow lagoons not freely communicating with the sea. The lowest beds (*Cleistopora* Zone) are dark, thinly bedded, and often associated with shales, while those of the *Zaphrentis* Zone are shelly rocks, usually dark in colour, and used for road-making and building. In the *Syringothyris* and *Seminula* zones there are white oolitic rocks, and in the *Dibunophyllum* zone, limestones in which corals are especially abundant are sometimes associated with shales and even grits, foreshadowing the oncoming of the Millstone Grit. Dolomite is extensively developed in the middle zones of the formation, especially in the eastern part of the South Wales Coalfield.

The rock thins out in a remarkable manner when traced from south to north and from west to east—that is in the direction of St. George's Land, as the following figures will show:—

Variation in the thickness of the Carboniferous Limestone in the South-Western Province.

Thickness in feet; from south to north	Mendip area 3,000	Clifton 2,400	Wickwar 1,670	Forest of Dean 6,000
Thickness in feet; from west to east	Gower Peninsular 3,000	Cardiff & Newport 1,000	Near Pontypool 100*	

North Wales, Staffordshire, and Derbyshire.—The outcrops of Carboniferous Limestone in Flintshire and Denbighshire, in Staffordshire, and in Derbyshire, may be considered together, because they are parts of a large area of limestone, most of which is concealed beneath the newer rocks of the Cheshire plain, and the limestones are, in general, similar in character throughout.

This region, as we have already seen, was not submerged until later than the South-western Province, and the Carboniferous Limestone of the north represents only the upper part

---

* Owing to overlap by the Millstone Grit (see Fig. 15) the full thickness of the limestone is not exposed here.

(*Seminula* Zone and *Dibunophyllum* Zone) of the south. The rocks consist mostly of dark and light shelly-, coral-, and crinoidal-limestones.

The long, comparatively narrow outcrop of Carboniferous Limestone that forms the western margin of the coalfield of North Wales is of interest from the part played by the rock in the deposition of the lead and zinc ores for which the district was once famous (see page 357). The dark limestones in the neighbourhood of Holywell are known as *Aberdo Limestone* because they were formerly considered to be like the Liassic limestone of Aberthaw in Glamorgan, which is renowned for its cement making qualities; *Fig.* 76. Cement is also made at Caerwys, using Carboniferous Limestone and a red boulder clay (a glacial deposit, see page 288) that occurs in the vicinity.

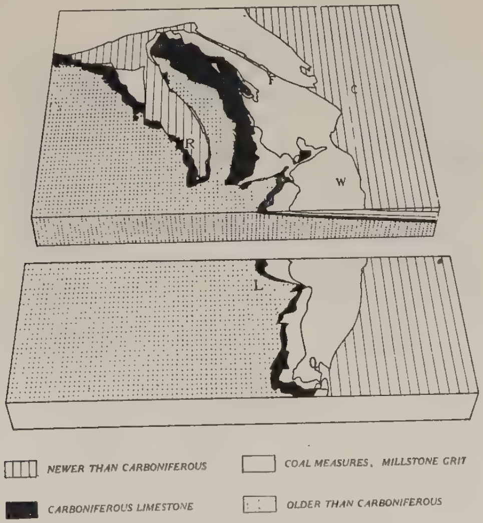

FIG. 75.—THE STRUCTURE OF THE NORTH WALES COALFIELD.

The Carboniferous rocks of Flintshire and Denbighshire pass towards the east beneath a covering of newer strata, and the Carboniferous Limestone forms a relatively narrow strip along the western margin of the coalfield and another strip fringes the Vale of Clwyd. R, Ruthin; F, Flint; W, Wrexham; C, Chester; L, Llangollen; O, Oswestry.

The outcrop comes to an end at Llanymynech Hill, near Oswestry, and in that area it has been extensively quarried. The rock was formerly sent to the Staffordshire iron works for use as flux, or was burnt for agricultural lime, but many of the quarries are now worked for dolomite [14]. Some of the coral limestones make handsome ornamental stones, and certain pink and yellow limestones at Llanymynech are said to be capable of taking a good polish. The more westerly of the North Wales outcrops forms the hills that rise steeply from the alluvial plains at the mouth of the Vale of Clwyd, and it ends in the imposing cliffs of Great Ormes Head at Llandudno [45, 46].

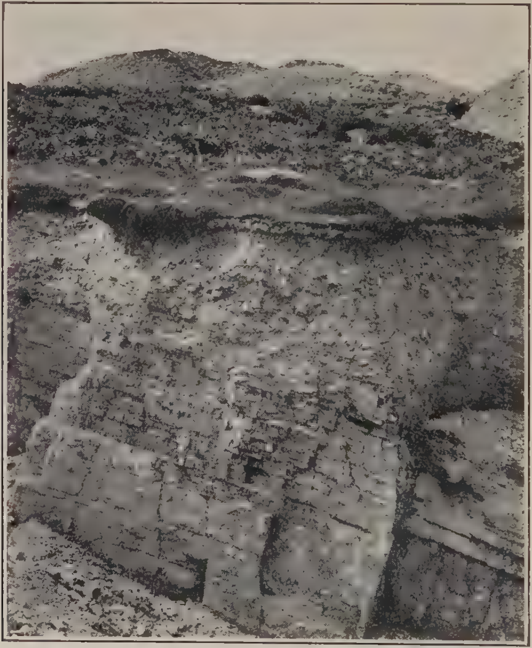

FIG. 76.—GLACIAL DEPOSITS ON LIMESTONE.

The Carboniferous Limestone of Halkyn Mountain, Flintshire; the rock has been used in the manufacture of hydraulic cement. (Reproduced by permission of the Director of the Geological Survey.)

From its striking development in the Peak District of Derbyshire the Carboniferous Limestone was formerly called the *Mountain Limestone,* a name that is still frequently used. As in other regions, the rock varies greatly in character, and includes varieties composed of broken shells, of closely packed almost entire shells, of crinoid fragments, or of corals and coral debris. Foraminifera are abundant, but the fossils have often been more or less completely destroyed by the recrystallisation of the limestone, or by dolomitisation.

In Derbyshire there were occasional outbursts of volcanic activity during Carboniferous Limestone times, and, associated with the limestone, there are lavas and intruded igneous rocks (locally called toadstones) and volcanic " ashes." Where in contact with the igneous rocks the limestone has sometimes been converted into a crystalline marble, and the fossils have been destroyed; this is the case for example in the Peak Forest District [15].

Yorkshire and the south of Lancashire. — Around Clitheroe and towards the centre of the Northern Province the limestone is very thick, and includes representatives of the four upper fossil-zones. In this district there are peculiar reef-like masses of shelly limestone consisting mostly of brachiopods; they appear to have originated as shell-banks in the Carboniferous Limestone Sea, and, being more resistant to weathering than the normal limestones, tend to stand out as low rounded hills.

Running for several miles in a south-easterly direction a little to the north of Settle, is a fault—the Craven Fault—to the north-east of which there is a remarkable change in the character of the limestone; but whether this change is in any way connected with circumstances that are due to the fault, or whether it is merely a coincidence, is not certain [27]. On the north-eastern side of the fault the Lower Carboniferous rocks are much thinner, and they include alternations of limestone, sandstone, and shale. The lowest limestone is known as the *Great Scar Limestone* which is about 600 feet thick. The upper part of the formation is here of a sandy and shaly character, with thin bands of limestone, and it is known as the *Yoredale Beds,* the fossils of which are identical with those of part of the *Dibunophyllum* Zone of the South-western Province.

North Lancashire, Westmorland, and the Lake District.—In this region there are representatives of at least the three upper zones of the South-western Province. The lowest Carboniferous beds are shales and conglomerates (seen in Ravenstone Dale and near Shap), and above them are highly magnesian limestones, which were, in all probability, laid down in the shallow waters of large lagoons, in which algæ such as *Solenopora* thrived to such an extent that their calcareous skeletal remains often make up the bulk of the rock. The upper beds represent the *Dibunophyllum* Zone of the south, and are very rich in the shells of foraminifera [1 a]. In West Cumberland there at least seven distinct limestones, separated by shales and sandstones, representing the *Dibunophyllum* Zone and part of the *Seminula* Zone [27 a].

Northumberland and the Scottish borders. — Between Northumberland and the regions already described there seems to have been, during part of the Carboniferous Limestone time, a ridge partially separating the two areas of deposition.

It was only from 10 to 20 miles wide, and extended in a north easterly direction from the coast south of St. Abb's Head by way of Appleby. As the site of the ridge (which, of course, does not now exist as a ridge) is approached from the south, the limestone becomes thinner, and passing northwards from it, the Carboniferous Limestone Series again thickens, although the thickness is partly due to the intercalation of beds of shale and sandstone; near Alston, for example, where the series has a thickness of about 1,600 feet, there are at least twelve distinct limestone bands. Geologically lower beds also begin to appear, and by the time the Scottish border is reached, the thickness has increased to about 2,000 feet.

In this region, the Carboniferous Limestone series comprises the following sub-divisions :—

Upper Calcareous division—mostly sandstones and shales with coal seams and very few beds of marine limestone.

Lower Calcareous division—sandstones and shales with coal seams, and many beds of marine limestone; local names have been given to some of the limestones—for example, *Oxford Limestone, Redesdale Limestone, Hardraw Limestone.*

Carbonaceous division (or *Scremerston Beds*)—consisting principally of sandstones and shales with coal seams, and a few thin limestones.

Fell Sandstone Group—massive grits with shales giving rise to the craggy hills of the west of Northumberland.

Cement Stone Group—sandstones and shales with beds of hard cream coloured earthy limestone, called, from the use to which it has been put, " cement stone."

Conglomerate Group—this is developed locally, as around the Cheviot Hills; it consists of reddish brown conglomerate, and by some is regarded as the topmost division of the Old Red Sandstone.

In the abundance of sandy and shaly sediments and in the presence of coal seams, these strata differ markedly from the thick and continuous Carboniferous limestones of the south-west, of which they are the time-equivalents, and they indicate the proximity of the shore of a great land-mass, from which the products of rock weathering were washed in abundance into the neighbouring sea.

Scotland.—The Lower Carboniferous rocks of the Central Lowlands of Scotland (between the Firth of Forth and the Firth of Clyde) consist, like those of Northumberland and the border regions, of sandstone, shales, and coal seams, with subordinate limestones. The coal seams are thicker than in Northumberland, and the limestones, which are comparatively thin, are almost confined to the upper part of the Series.

The limestones are, therefore, younger than most of the Carboniferous Limestone of England, and the Carbonaceous group of Northumberland is represented in the central lowlands by oil-shales—that is to say, shales so rich in bituminous matter as to yield petroleum-like products when suitably distilled. Lava and volcanic ashes are well displayed among the Scottish Lower Carboniferous rocks.

Ireland.—The Carboniferous Limestone series is well-represented in Ireland, where it occupies an area nearly three times as great as the combined outcrops in Great Britain (*Fig.* 65). As a result of folding, a few isolated areas of Millstone Grit and Coal Measures occur, and some older rocks rise from beneath the limestone, but apart from these, the central region of the island consists essentially of Carboniferous Limestone, although owing to the low-lying condition of much of the country and the widespread covering of superficial deposits, including peat, actual exposures are not abundant. The best exposures occur in the west, south, and east.

When traced from south to north, the Lower Carboniferous Series of Ireland exhibits changes similar to those seen in Great Britain. In the extreme south-west there are dark shales with some calcareous beds resembling the strata of similar age in Devonshire; near Cork, massive limestones begin to make up the greater part of the Formation, which in the counties of Clare and Galway consists almost entirely of limestone and is about 3,000 feet thick, while in the north, the rocks resemble those of the Scottish border regions and the central lowlands, for sandy and shaly beds predominate over limestones, and coal seams are present.

Commercial uses of the Carboniferous Limestone.—The Carboniferous Limestone provides more industrial limestone than any other geological formation in this country, and the rock is put to a great many uses. The bulk is used as a flux in blast furnaces, for lime- and cement-making, and for roadstone, while some of the very pure varieties are suitable for chemical manufacturing processes, but no useful purpose would be served by attempting to enumerate all the localities from which the various kinds are

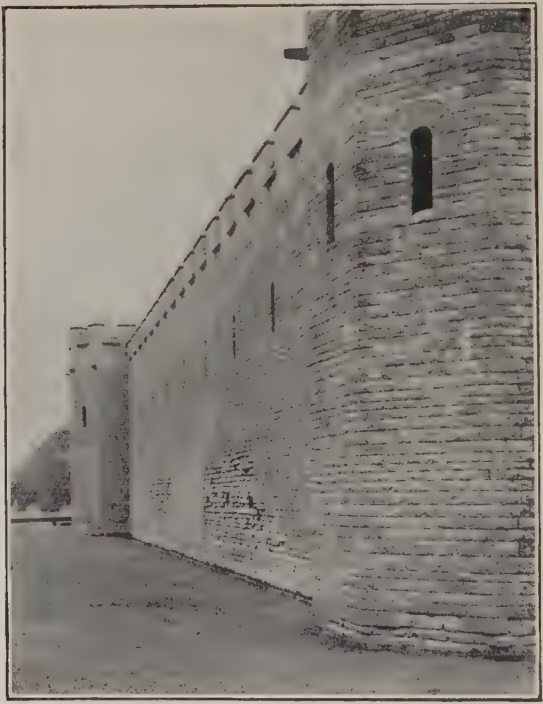

FIG. 77.—THE WALLS OF CARDIFF CASTLE.

The main part of the wall has been built within the last three or four years, and is of Carboniferous Limestone from Wenvoe, Glamorgan. It has been erected upon the remains of the Roman wall, portions of which, built of limestone of Liassic age, can be seen forming the lower part of the structure. (*Photo W.E.H.*)

obtained; other objects fashioned from the rock include gate-posts, curbs, and (when it is fissile and sufficiently resistant to weathering) gravestones. Near Oswestry certain beds are quarried for making mangers for the boxes in which valuable horses are kept, because the rock is more absorbent of moisture than the glazed earthenware that is frequently used [14].

In many places the Carboniferous Limestone has been and is still used as a building stone (*Fig.* 77), while certain local varieties that are capable of taking a high polish have been used as decorative marbles, probably to a greater extent than is generally realised [16-18]. Such varieties belong to three main types :—

(*a*) Those which contain fossils that give the rock a characteristic pattern.
(*b*) Varieties that are black, either uniformly, or veined with white; the black colour is due to the presence of much carbonaceous matter resulting from the decomposition of organic remains.
(*c*) Coloured varieties, such as those which are pink or red owing to the presence of iron compounds; the latter have in many cases been introduced by infiltration from ferruginous deposits (such as some of the sandstones and marls of the Trias) that once rested on the limestone but have since been removed by denudation.

It should be borne in mind that these rocks are not true marbles, which are metamorphic rocks (see page 3), but, being capable of taking a high and durable polish they serve the same purpose as the crystalline limestones, and are called " marble " for trade purposes.

Among the fossiliferous marbles, some consist principally of coral remains and others of shells or of crinoid stems. The coral limestones include the *Frosterley Marble,* so called from the place of that name on the banks of the River Wear in Durham (*Figs.* 78 and 214). The rock, which occurs near the top of the Carboniferous Limestone Series, is rich in the corals *Dibunophyllum* and *Lithostrotion,* the light coloured skeletons of which are conspicuous in a dark grey ground-mass. Frosterley Marble was one of the earliest to be used in the north of England for church decoration, as for example in Durham Cathedral during the 13th century, and in the pavement of York Minster (14th century): its use was contemporary with that of the Purbeck Marble in the south of England. In recent years it has been used in the Cathedrals at Peterborough, Bristol, and Bombay.

Certain beds of the *Scar Limestone* near Alston are rich in the coral *Lonsdaleia duplicata,* and might be much more extensively used for ornamental work especially where large slabs are not required.

Crinoidal " marbles " are well developed near Middleton in Derbyshire, where the varieties of *Hopton Wood Stone* are extensively quarried for all kinds of indoor and outdoor structural and ornamental work (*Fig.* 23). A grey limestone with large crinoid fragments (*Monyash Marble*) that occurs near Bakewell, was used in the corridors of the Imperial Institute, and a brownish-grey rock in the *Upper Scar Limestone* at Dent in Yorkshire, is used for church decoration. The *Halkyn Marble* of Flintshire is a crinoidal limestone, and the so-called *Petit Granit* of Belgium is also a limestone of Lower Carboniferous age that consists of the debris of crinoids, corals, and shells in a dark, almost black matrix (*Fig.* 79). It somewhat resembles a dark grey granite, hence the name; some varieties are used for building stone, and others as " marble " for objects such as table tops, and, in conjunction with coloured marbles, in ecclesiastical decoration, as for example, in the chancel of Bristol Cathedral. Some of the limestone at Penmon, near Beaumaris (Anglesey) which is compact, fine grained, and takes a good polish, has been used as a decorative stone (light brown with darker veins and patches), although the rock has more generally been used for building purposes (*e.g.,* Beaumaris Castle).

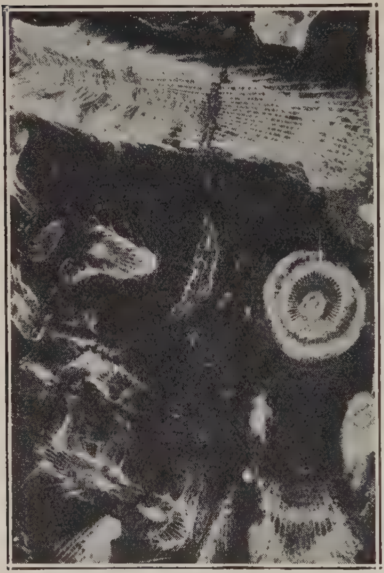

FIG. 78.—FROSTERLEY MARBLE.

Carboniferous Limestone with corals, from Frosterley, near Durham; slightly reduced.

Dark coloured limestones with shells (mostly brachiopods) that occur in Pembrokeshire, have been used locally for mantelpieces and similar objects, while the dark limestones of Poolvash, in the Isle of Man, have also been used as a " marble "; the steps of St. Paul's Cathedral (about 1668) were made from *Poolvash Marble,* the gift of the then Bishop of Sodor and Man.

A deep red fine-grained limestone (*Duke's Red*) occurring in thin beds at Rowsley, Derbyshire, was at one time so much esteemed that it was feared that the supply would be exhausted, and a former Duke of Devonshire had all the available stone quarried and stored; it was used, among other places, in St. John's Chapel, Cambridge. A dark brown limestone with parallel reddish veins, at Bakewell in Derbyshire, is so much like rosewood as to be sometimes mistaken for that wood, and has been much used for mantelpieces.

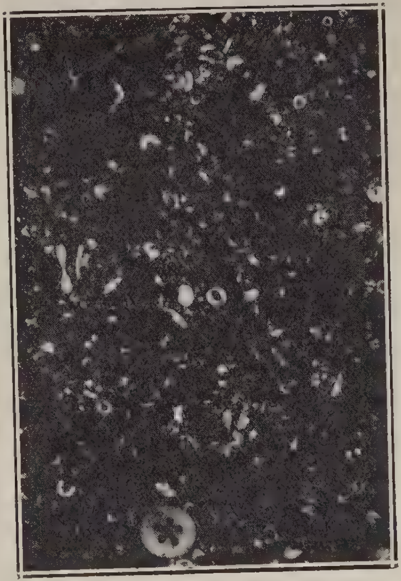

FIG. 79.—" PETIT GRANIT."
Carboniferous Limestone with crinoid fragments from Belgium; natural size.

In Ireland, black " marbles " of considerable commercial importance occur in a number of places, such as Kildare, Limerick and Kilkenny; black *Kilkenny Marble* is widely used, and in this country is to be seen in Brompton Oratory, and in the Cathedrals at Wells and Worcester. *Irish Dove* is a blue-grey rock with white veins found at Fermoy in Co. Cork; *Armagh Red* is a compact purplish brown stone, which takes a very high polish, has been used for mantelpieces and for internal decoration (the Cathedral at Armagh and St. John's Chapel, Cambridge). *Cork Red* is a mottled pink and brown crinoidal marble from near Queenstown; it was used in the pulpit columns at St. Paul's Cathedral, and in one of the chapels in the Roman Catholic Cathedral at Westminster.

Dolomite in the Carboniferous Limestone.—The phenomenon of dolomitisation has already been referred to (page 42), but dolomitic limestones are of sufficient importance in the Carboniferous Series to be separately discussed at this juncture. Although dolomitic or magnesian limestones are fairly widely distributed in the Carboniferous Limestone, masses of dolomite chemically suitable and large enough to be worked for refractory purposes are not common, but they occur at Porthywaen (near Oswestry), at Clydach (near Abergavenny), and other places in South Wales, and near Skipton in Yorkshire [19]. In parts of Derbyshire, Leicestershire [20] and the Forest of Dean, the Carboniferous Limestone is more regularly dolomitised, but there does not appear to have been any organised search for rock suitable for exploitation.

Most of the dolomite is of secondary origin, that is to say, it results from the alteration of a normal limestone, and, quoting from Dr. T. Franklin Sibly's observations in one of the Special Reports on the Mineral Resources of Great Britain [21] issued by the Geological Survey,

> "according to the period in the life of the rock at which dolomitization was produced, secondary dolomitization may be distinguished as :—
>
> (1) *Contemporaneous dolomites:* those produced by the alteration of the original limestone, shortly after its deposition, by the influence of magnesium salts in the waters of the sea in which it was deposited.
>
> (2) *Subsequent dolomites:* those produced by the alteration of the original limestone by the influence of magnesian waters which penetrated the rock at any time subsequent to the period of original deposition."

The persistence of beds of dolomitic rock over wide areas generally indicates contemporaneous dolomitisation, but subsequent dolomites usually occur in vein-like or irregular patches. Again quoting Dr. Sibly :—

> "In most cases of contemporaneous dolomitization, a widespread calcareous deposit was altered more or less uniformly throughout its extent during its exposure to the action of sea-water. In the process of subsequent dolomitization, however, access was afforded to infiltrating magnesian waters by joints, bedding-planes and fault-fissures in an already consolidated limestone, and as a frequent consequence the dolomitization is confined to the rock bordering those planes of division (typical vein-dolomitization). But in some cases of subsequent dolomitization, diffuse permeation of the rock-mass by the magnesian waters has resulted in the uniform dolomitization of great masses of limestone. An important instance of this latter phenomenon is found in the beds of

the *Crease Limestone* in the Forest of Dean, which have been dolomitized in their entirety over a large part of the district" [see also 2, 19, 21 & 22].

It is interesting to note that where iron ores (to be mentioned later) are developed in the Carboniferous Limestone, the rock in which they occur is usually highly dolomitised.

Prior to the introduction of the "Basic Process"* of steel making, dolomite was regarded rather as a material to be avoided in the quarrying of limestone. In the case of the Porthywaen occurrence, for example, although Murchison had drawn attention to the presence of magnesia in the limestone as far back as 1839, only the purer limestone was worked, and the impure parts —called "rottenstone"† by the quarrymen—were left behind. When, however, as a result of complaints concerning the quality of some of the lime that was being made, the rock was analysed, it was found that the unsatisfactory lime was really calcined dolomite, and as the Basic Process had then been introduced, the hitherto neglected "rottenstone" became of considerable importance, and the output of the calcined dolomite from the district has in some years reached 30,000 tons [19, p. 206].

Limestone in the Upper Carboniferous Rocks.—We have seen that the Carboniferous Period as a whole was one of long continued, although intermittent, subsidence, but the formation of the Carboniferous Limestone was brought to a close by the commencement of a period of rather rapid upheaval. The rivers of the neighbouring lands flowed down steeper slopes than hitherto, and they were able to carry not only mud but coarse sand and even pebbles, forming, in the adjacent sea, deposits of conglomerate, grit, and sandstone, such as those which constitute the Millstone Grit of many districts. The upward movement which gave rise to the formation of the Millstone Grit eventually ceased, and a slow downward movement again set in. The coarse deposits of the Millstone Grit were due to the work of streams that flowed down steep slopes, and that were, in consequence, actively eroding their beds, but as time went on and the general level of the land over which they flowed was lowered, the streams lost the power of shifting pebbles and sand, and carried vast quantities of mud into the sea.

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* In the making of steel, one of the functions of the material with which the furnace is lined is to combine with certain of the impurities present in the ore or in the iron that is being treated. The material used in the lining has of necessity to be able to withstand very great heat, and, originally, mixtures of silica and clay, or bricks made of silica were used. The silica combined with most of the carbon, manganese, and silica in the iron, but did not affect the sulphur and phosphorus that may have been present. About 1878 it was found that a lining of burnt or calcined dolomite combined with the oxides of phosphorus, sulphur, and silicon, thus removing very undesirable impurities, and at the same time yielding a slag, that, on account of the phosphorus it contains is suitable for use as a fertiliser and is known as "basic slag." Owing to the part played by the lining in the chemical reactions involved, the operation is known as the "acid process" when the lining is siliceous, and the "basic process" when it is dolomitic.

† This is not the material usually called rottenstone (see page 48) which is a friable material representing the insoluble residue of a weathered limestone.

As we have seen, the sediment which was continually pouring into what remained of the old Carboniferous Limestone sea eventually filled it up, and this country, together with a large part of north-western Europe, was converted into an area of swampy mud flats, not much above sea level. On these mud flats, and on the adjacent low-lying land, grew the forest trees, the remains of which are now coal seams, but the story of the accumulation of the Coal Measures and of the formation of coal has been told elsewhere, and does not further concern us here [23].

It will be realised that conditions such as those described —conditions favourable to the deposition of pebbles, sand, and mud (the latter largely of freshwater origin), were not favourable to the formation of limestone, and we find, accordingly, that although the Upper Carboniferous rocks are in places as much as ten thousand feet in thickness, limestones are almost entirely absent.

In the coalfields of Staffordshire and North Wales, the upper part of the Coal Measures consists largely of red and purple clays, shales, and sandstones, devoid of workable coal seams. The red beds appear to owe their origin to the fact that towards the close of Coal Measure times there was a general uplift of the British region; the swamps that, during the coal-forest times, had existed to the north of St. George's Land were isolated from the sea, and local shallow lakes or lagoons were formed; in some of these the water became stagnant owing to the lack of free circulation. Iron seems to have been peculiarly abundant in the coal measure muds, and where the oxidising influence of the air was greater than the reducing action of decaying vegetation, it was precipitated, largely in the form of compounds similar to those formed when iron rusts.

The redness of the rocks is, as in the case of the red strata of the Old Red Sandstone, due to the fact that each grain is coated with a thin film of oxide of iron, deposited as the grain settled out from water heavily charged with iron, and it is this abundance of iron which suggests that the water was stagnant, because such conditions would not be likely to occur in water basins through which there was free circulation, or which communicated with the sea.

Here and there among the red beds of the upper part of the Coal Measures there are thin limestones, usually of an earthy compact character and quite unlike the ordinary marine Carboniferous Limestone. The only fossils they contain are the shells of minute crustacea (Entomostraca), and the little spiral shells of the marine worm, *Spirorbis*. Members of the genus *Spirorbis* have existed from Ordovician times to the present day; they encase themselves in a spirally coiled protecting tube—not much more than an eighth of an inch in diameter—and the recent forms usually live attached to seaweed; the shells are frequently to be seen on the leaves of *Cordaites* and other Coal Measure plants. *Spirorbis*-limestones occur in the *Keele Beds* of the Staffordshire Coalfield, and in the corresponding strata in the coalfields of Warwickshire, Flintshire, and Denbighshire; they are also present in the Red Coal Measures of Cumberland, the Canonbie

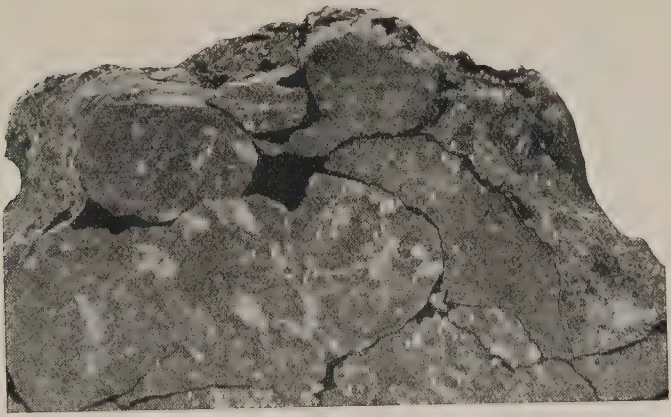

FIG. 80.—"COAL BALLS."

Nodules of calcareous material present in certain coal seams. In this specimen the mass consists of a number of small nodules with a little coal between them; photograph about one-fourth natural size.

Coalfield (north of Carlisle), and in Central Scotland [24-6]. These limestones are usually only a few inches thick, but are occasionally from 2 to 6 feet.

Although of considerable importance in connection with the correlation of the Upper Carboniferous rocks, the *Spirorbis*-limestones are of little commercial importance; in a few places the rock has been burnt for lime, as for example at Illey Brook (S. Staffordshire) where there are many old workings in a dirty white or pale blue limestone with *Spirorbis*.

Coal-balls.—Of considerable scientific interest are the rounded masses of calcareous material (known as "coal-balls") found actually within the body of certain coal seams, and sometimes in the immediately overlying shales, for in them, plant-structures have been preserved in a remarkable manner [23, 51, 52].

In diameter the nodules vary from a fraction of an inch up to more than a foot, although most of them are about as large as potatoes or cocoanuts; *Fig.* 80. When sawn across and washed with acid the material is seen to be greyish brown in colour. "Coal-balls" appear to represent portions of the original coal substance in which the still undecomposed plant fragments were permeated by water containing in solution the carbonates of lime and magnesia—for those carbonates constitute about 90 per cent. of the coal-balls, the remainder being mostly manganese carbonate, iron carbonate, iron oxide, pyrites, clay, and carbon. In coal-balls, not only are the cavities of the original plant cells filled with mineral matter, but the cell walls themselves may have been mineralised. The change took place so gradually and so thoroughly that for every molecule of the organic substance of the woody tissue that was removed, a molecule of inorganic material was deposited in the same place, with the result that the minute structure of the fossil is faithfully preserved (*Fig.* 81). This is a matter of great importance, because, not only has much light been thrown upon the structures and affinities of plants represented in the coal-balls, but the excellently preserved material has assisted in the interpretation of the more fragmentary and often ill-preserved plant structures present in many parts of the coal itself.

Coal-balls undoubtedly represent mineralised portions of the original coal substance, and are not stones that have been washed into the coal seam, because the plant-remains in them are similar in nature and in arrangement to those seen in the coal itself, and in some cases large fragments of plant tissue appear to be preserved partly in a coal-ball and partly in the adjacent coal.

It is interesting to note that the seams in which coal-balls occur, have, above them, deposits containing *marine* shells, indicating that it was the water of the sea that brought to a close the growth of the forest that provided the vegetable debris from the alteration of which the coal seam has resulted. As a rule the deposition of the coal-bearing strata was associated with fresh water although brackish water conditions occasionally prevailed, and in the presence of marine beds above the seams where coal-balls occur we have the explanation both of the source of the mineralising solutions, and also of the very limited distribution of coal-balls.

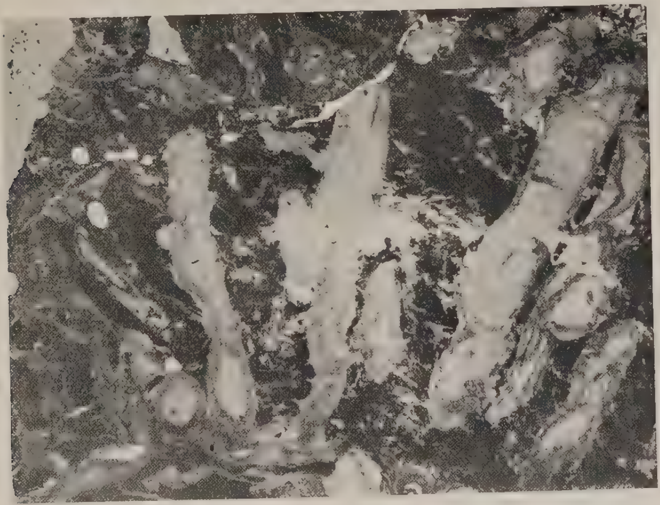

FIG. 81.—PLANT STRUCTURES PRESERVED IN COAL BALLS.

Photograph, natural size, of a thin section of a coal ball showing plant roots penetrating vegetable debris.

In the English Coal Measures coal-balls are practically confined to Lancashire and Yorkshire, but they have also been recorded from rocks of Carboniferous Limestone age in the south of Scotland. They include both calcareous and dolomitic varieties: one specimen from Bacup contained 51.2 per cent. of calcium carbonate, and 42.8 per cent. of magnesium carbonate, while in another from Stalybridge the proportions were 87.8 per cent. and 6.2 per cent. respectively [51].

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CHAPTER VIII.

LIMESTONE IN THE PERMIAN AND TRIASSIC SYSTEMS OF ROCKS.

> "From the great law of change we are not free:
> And what we seem to-night we shall not be
> Upon to-morrow dawn. . . .
> And that is solid earth, that once was sea;
> Seas, in their turn retreating from the shore
> Make solid land, what ocean was before."
>
> OVID, *Metamorphoses* XV.,* Dryden's translation.

The New Red Sandstone group of rocks.—Between the Coal Measures and the marine beds of the Lias there occurs a group of variable strata (principally marls, sandstones, and conglomerates, but including also occasional limestones) of which the prevailing colour is red or yellow. They were classed together by the older geologists as "New Red Sandstone" and were thus distinguished from the "Old Red Sandstone" which occurs beneath the rocks of the Carboniferous System.

In 1841, Murchison suggested that the New Red Sandstone really included two distinct sets of deposits, an older set to which he gave the name *Permian,* from the Russian province of Perm where the rocks are well displayed, and a newer set called *Trias,* because in Germany, where the name was proposed by F. A. von Alberti in 1834, the rocks exhibit a three-fold stratigraphical division.

In the Permian System were included certain red marls and sandstones associated with the Midland Coalfields, and also a group of marls, sandstones, and conglomerates occurring in South Devonshire, near Teignmouth and Exeter, together with similar rocks occurring as a narrow outcrop from Kirkby Stephen by way of Penrith towards Carlisle, and a long outcrop of marls and magnesian limestones extending from Nottingham more or less northward to Knaresborough and the River Tees, and from thence curving eastward to the sea between Hartlepool and South Shields (*Fig.* 82). Rocks regarded as Permian also occur in the

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* It is interesting to note that although Ovid wrote at the beginning of the Christian Era his "Metamorphoses" were based upon views expressed by the Greek philosopher, Pythagoras, in the 6th century B.C.

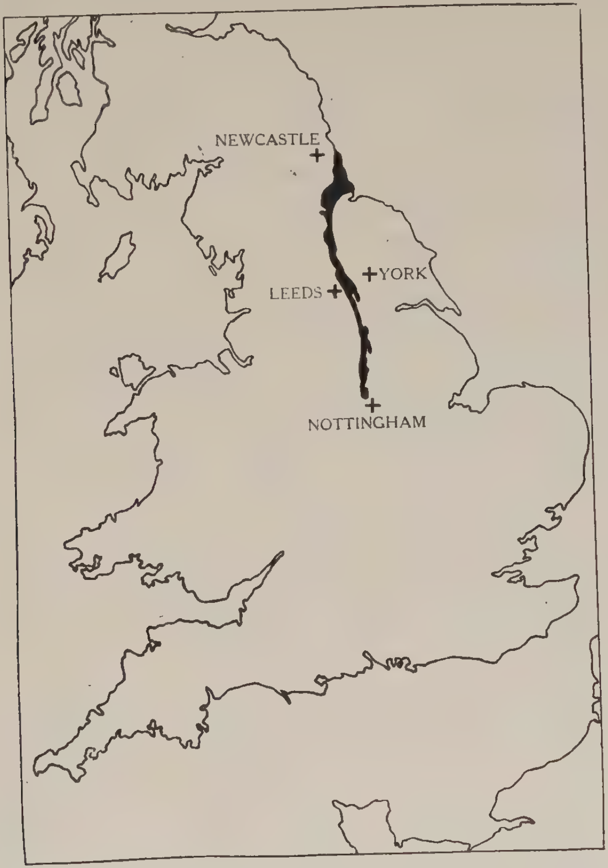

FIG. 82.—THE OUTCROP OF THE PERMIAN MAGNESIAN LIMESTONE.

Isle of Man, at three places in Ireland (Cultra on Belfast Lough, Ardtrea in Tyrone, and at Armagh) and in Scotland (the shires of Dumfries, Ayr, and Moray).

Owing to their varied lithological character and to the general scarcity of fossils, the rocks of the " New Red Sandstone " proved very difficult to classify and correlate, and in recent years, Dr. R. L. Sherlock [1] has shown that there are reasons for supposing that, at least in this country, the differences between the beds classified as Permian and as Triassic, are, to a large extent, due to the conditions of deposition, and do not indicate *time*-divisions, as do, for example, the Arenig, Llandeilo, and Bala Series of the Ordovician System. If this is the case there are no true Permian Beds in this country. The details of this interesting discussion do not concern us here, for it is only in one area that limestone is conspicuous in beds of New Red Sandstone age (the long outcrop on the east of the Pennines already referred to); the rock is usually highly dolomitic, and is generally known as "The Magnesian Limestone."

Geographical conditions in New Red Sandstone times.—As the coal-bearing strata of this country are traced upwards from their base the coal seams tend to become thinner and less frequent until they finally disappear, indicating the on-coming of climatic conditions unfavourable to the luxuriant growth of vegetation and to the preservation of the remains of dead plants. These climatic changes were the outcome of a new and widespread upheaval which caused large parts of the swampy area to become dry land, and the forests to give place to arid deserts.

One result of the uplift was that the Carboniferous and older rocks were thrown into folds—some, like those in South Wales (*Fig.* 83), trending east to west, and others like those in the north of England (the Pennine area) trending north and south. During the process of rock-folding, mountain chains were built up somewhere to the south and south-west of the British area, and since the wet winds came, as they do now, from the south-west, most of the moisture was deposited on the south side of the range and it was because the winds that passed over the land to the north were dry that the desert conditions already referred to prevailed.

It was because of the abnormal conditions of rock-weathering that prevail in desert regions that the loose material resulting from the denudation of the Coal Measures and other rocks that were then exposed was not carried away by streams to the sea, but was scattered by the wind and by the occasional torrential rains that from time to time gave rise to temporary lakes, and was spread over the land as dust, sand, or more or less angular rock fragments, filling the hollows in the surface, and choking such lakes as may have existed, with deposits that eventually gave rise to marl, sandstone, and breccia; *Fig.* 90.

Towards the middle of the Permian "phase," as we may for present purposes call it, in view of Sherlock's findings to which reference was made on a previous page, the rock folding and consequent elevation appear to have ceased, locally at least, and during a period of subsidence, the northern parts of England were invaded by the waters of the sea (which lay to the east) forming a large land-locked gulf in which marls and magnesian limestones were deposited. Some of the limestones were ordinary marine deposits, but others were chemical precipitates from water saturated with mineral salts.

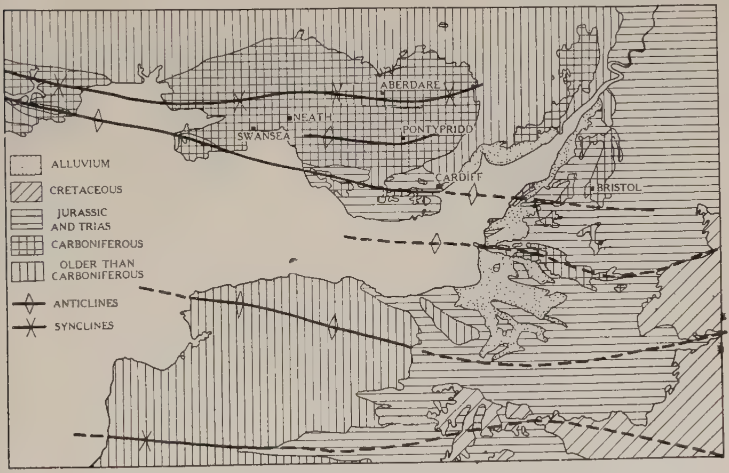
ABERDARE
NEATH
SWANSEA
PONTYPRIDD
CARDIFF
BRISTOL
ALLUVIUM
CRETACEOUS
JURASSIC AND TRIAS
CARBONIFEROUS
OLDER THAN CARBONIFEROUS
ANTICLINES
SYNCLINES

FIG. 83.—GEOLOGICAL SKETCH MAP OF THE SOUTH-WEST OF ENGLAND AND WALES,

illustrating the east to west trend of the folds into which the older rocks were thrown soon after the close of the Carboniferous period. The area in Devonshire indicated as older than Carboniferous, includes also the outcrop of the Culm Measures which are of Upper Carboniferous age.

As the period drew to a close, slight local movements in the earth's crust converted the gulf into a great inland salt lake, resembling in some respects the present Caspian Sea (*Fig.* 84). Dust blown into, and mud washed into that sea gave rise to deposits of marl; and as parts of the basin dried up, some of the substances dissolved in the water were left behind as beds of common salt and gypsum, which are characteristic of the highest Permian strata in this country.

That the final drying up of the Permian Sea was due to increasingly arid conditions rather than to uplift, is suggested by the fact that the highest limestones do not extend so far to the west as the lower limestones, indicating a shrinkage of the area covered by the sea.

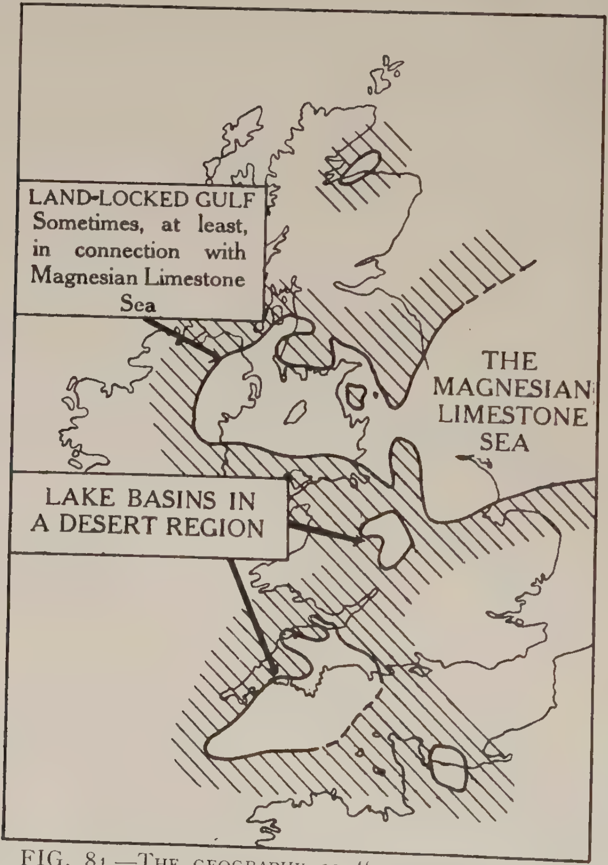
LAND-LOCKED GULF
Sometimes, at least, in connection with Magnesian Limestone Sea
THE MAGNESIAN LIMESTONE SEA
LAKE BASINS IN A DESERT REGION

FIG. 84.—THE GEOGRAPHY OF "MAGNESIAN LIMESTONE" TIMES (after A. J. Jukes-Browne).

Life of the Permian "phase."—It will be realised from the foregoing résumé of the physiography of Permian times that conditions were in general unfavourable to life, but enough fossils have been preserved to indicate the nature of the life upon land, in the open sea, and in the inland lakes. On the whole, the flora resembled that of the later part of Coal Measure times, but a number of plant types that became more important in the succeeding periods had already made their appearance. Amphibians and reptiles of moderate size and comparatively simple organisation were abundant, and there were many fishes, but none of the plants or vertebrates contributed to the formation of limestone.

The typical marine fauna is found only in the south and east of Europe and in the adjacent parts of Asia, and it comprises many genera of bryozoa, brachiopods, and molluscs (including the earliest members of the ammonite group). In the land-locked Permian Sea of the British area there existed an impoverished remnant of the Upper Carboniferous fauna; it included a few molluscs, and some of the Carboniferous brachiopod genera, but the number of species was very much reduced as compared with the fauna of preceding periods from the Ordovician onward, and the individuals were often stunted in growth and comparatively few in number. In some parts of the Magnesian Limestone the bryozoan, *Fenestella,* is an important rock forming organism.

The Magnesian Limestone Series.—The narrow outcrop of the Magnesian Limestone runs from Nottingham, northwards by way of Mansfield, Doncaster, Pontefract, Knaresborough, and Darlington, and then widens out as it curves eastwards to the coast between the mouths of the Tyne and the Tees.

As the Series is followed from north to south it undergoes considerable lithological change. In the north (Northumberland and Durham) it consists mostly of magnesian limestones, with sandstones and shales below and marls with beds of salt above: there are three (Upper, Middle, and Lower) limestone groups.

In the North of Yorkshire the limestones become thinner and the marls thicker, while further south the Upper Limestones thin out, and the Permian strata as a whole are overlapped by the Trias, until in Nottinghamshire only the Lower Limestone group is present, with marls below and marls and sandstones above.

Near Kimberley (N.W. of Nottingham), the limestones give place to a thin, yellow, calcareous sandstone, and the general character of the deposit suggests an approach to the shore of the sea in which the sediments were laid down, so that the Magnesian Limestone is not likely to be encountered beneath the Trias further south. The rocks, however, dip to the east, in which direction the Permian strata pass beneath those of the Trias, and in borings at Newark in East Notts., and Haxley in Lincolnshire, thick magnesian (or dolomitic) limestones and marls were met with.

It is probable that the Pennine ridge was already in existence in Permian times because there does not appear to have been unrestricted communication between the "Magnesian Limestone Sea" and the country to the west of the Pennines. At some time, however, the water made its way into that region, for there are a few small areas of Permian strata, including magnesian limestones, in Lancashire and Cumberland.

The commercial uses of the Magnesian Limestone. — The Magnesian Limestone is of considerable commercial importance, and has been quarried in many places [2]. As a rule the Upper Limestones are thinly bedded, sometimes even flaggy, and they are less dolomitic than the Middle and Lower Limestones; they are not much used except in the north. The Lower Limestones yield the best building stones, especially in the south. For the most part the rocks are light in colour (white, cream, or yellowish brown), and, owing to the presence of rhombohedral crystals of calcite and dolomite, freshly broken surfaces are often sparkling, but this character rapidly disappears on exposure to the atmosphere. Most varieties are rough to the touch and in that respect resemble fine-grained sandstones.

A yellowish brown, rather coarse, crystalline stone at Mansfield Woodhouse was used in the lower part of the building of the Houses of Parliament, and in the Martyr's Memorial at Oxford. A very similar rock, containing a few scattered quartz grains, occurs at Bolsover Moor in Derbyshire, but owing to the abundance of joints and the irregularity of the bedding, large blocks cannot be obtained. The limestone at North Anston, Yorkshire, is compact and hard; it is of a yellow colour and duller than the Bolsover stone, while that at Roche Abbey (also in Yorkshire) has a sparkling sugar-like appearance when freshly fractured. The latter has been used for building and carving, but although large blocks can be obtained the supply is uncertain.

Near Mansfield (in Nottinghamshire) there are the *Mansfield Red Stone* and the *Mansfield White Stone* which contain much quartz sand and might almost be called sandstones, but as they represent a local development of the Magnesian Limestone and have a greater proportion of dolomitic cementing material than is usually found in sandstones they are best regarded as sandy dolomites; except in colour the two stones are almost identical. They have been extensively used, as for example in the Temple Bar Memorial, St. Pancras Hotel, The London Hippodrome, Burlington House (Piccadilly), the cathedrals of Ely and Chichester, and some of the colleges in Oxford and in Cambridge.

Taken as a whole, the Magnesian Limestones of the north-east of England are dense and strong, but although durable under certain conditions, they tend to decay in a smoky atmosphere, especially when deeply cut into mouldings, as proved to be the case in York Minster, the old church at Doncaster, and the Houses of Parliament. The more crystalline varieties appear to be better able to resist the decaying influence of the atmosphere, and the best varieties for building purposes are those in which the proportions of magnesium carbonate and calcium carbonate most nearly approach those of true dolomite [3].

Even in view of the comparatively rapid decay of the stone used in the Houses of Parliament it does not necessarily follow that the use of the Magnesian Limestone in town buildings is to be condemned, nor that the judgment of those who decided to use the stone was ill-founded. Magnesian Limestone from Bolsover Moor quarries was originally chosen, but when it was found impossible to maintain the supply, similar stone from Anston was substituted. The stone used in the Houses of Parliament was worked without inspection at the quarries, although it was known that some beds were of inferior quality, but in the case of the Museum of Practical Geology (Geological Survey) in Jermyn Street, which was built of stone from the same quarries and at about the same time, Sir H. T. de la Beche—then Director of the Survey—maintained a careful inspection during the whole time that the stone was being quarried, and scarcely any defective blocks were incorporated into his building, which has, in consequence, withstood the ravages of the atmosphere much better than have the Houses of Parliament.

The durability of some varieties of the Magnesian Limestone, when carefully selected and used under suitable conditions, is illustrated by the fact that Huddlestone Hall in Yorkshire, in which Magnesian Limestone from the neighbourhood was used, is still in a good state of preservation, although built in the 15th century. A more recent example of the use of *Huddlestone Stone* is the Memorial Cross at Charing Cross Station, London.

In the case of the Houses of Parliament, decay was first noticed only 10 years after the commencement of the building, and it was found that the stone in damp and sheltered situations suffered more than that which was exposed to the full force of the rain and the wind. This is because the decay resulted from the formation of magnesium sulphate owing to the action upon the magnesium carbonate of sulphurous gases in the air; the sulphate, being relatively soluble, was removed from surfaces washed by rain, but where the stone remained moist for a long time the solution penetrated into it, and during dry weather the crystallisation of the magnesium salt tended to the formation of minute cracks in the surface layers of the stone; see also page 376 and [4].

Although so characteristically magnesian as to have given rise to the stratigraphical name "*Magnesian Limestone,*" the rock is by no means uniformly dolomitic, and both magnesian and calcareous limestones, sharply defined one from the other, may occur in the same quarry, and some of the dolomites appear as ridges or knolls surrounded by ordinary calcareous limestones.

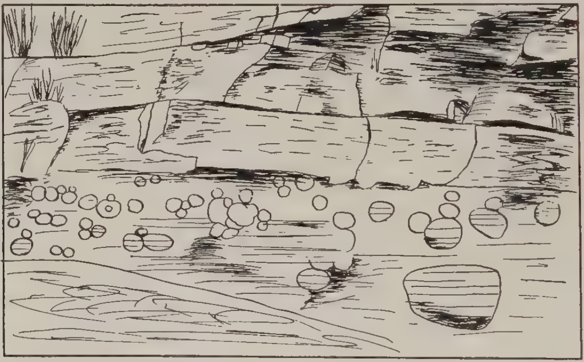

FIG. 85.—CONCRETIONS IN THE MAGNESIAN LIMESTONE, MARSDEN, DURHAM.

Diagram, after a photograph by Prof. E. J. Garwood, showing concretions developed in certain beds of the Magnesian Limestone, while adjacent beds are free from that structure.

The rock is not so extensively used as a " basic " refractory material as its name might lead one to suppose, because a good dolomitic refractory rock must be compact in texture, and many of the Durham Magnesian Limestones are earthy and porous. It is, however, quarried for that purpose at Coxhoe, Co. Durham (from the lower part of the Magnesian Limestone Series) and the same quarries also produce limestone for flux. The Fulwell Quarries near Sunderland, which have been worked for more than a century, yield a calcareous stone for lime-burning.

Dolomite for calcining and for making " basic bricks " is also quarried in Derbyshire, near Worksop, while from quarries in Yorkshire, near Shireoaks, the rock is more calcareous and is mostly burnt into lime for building and for agricultural purposes, or is used for roadstone.

Concretionary structures in the Magnesian Limestone Series.—An interesting feature of the Magnesian Limestone Series of Durham is that some of the beds exhibit concretionary structures to a remarkable degree. The concretionary beds are especially well seen between Sunderland and South Shields, and when fully developed the individual concretions are usually spherical and range in size from 3 inches to as much as two feet, but the smaller sizes are the most abundant (*Fig.* 85). Although really occurring in marls interstratified with limestone, the calcareous matter is sometimes so abundant as to form irregular masses of concretions from 20 to 30 feet thick with very little marl between them; the concretionary beds often pass laterally into well-stratified limestones.

The concretions occur in every stage of development, and the "immature" examples, which are usually cellular, consist of radially arranged rod-like structures and concentrically arranged bands, and bear a striking resemblance to certain massive corals and bryozoans (*Fig.* 86). In later stages of growth the interspaces were filled and the concretions became solid masses of limestone. Attention was drawn to the existence of these peculiar structures as long ago as 1826 when Adam Sedgwick described the Magnesian Limestone of the East of England in a series of communications to the Geological Society [5].

It has been pointed out that the beds in which the concretionary structures are best developed were probably more calcareous than the highest limestone of beds of the Durham Magnesian Limestone, and a large series of analyses of the rocks from various localities is given by Dr. C. T. Trechmann in a paper describing their lithology and composition [6]. They were also studied in detail by Professor Garwood, who pointed out that although the concretions contained on an average from 85 to 95 per cent. of calcium carbonate, and from 4 to 12 per cent. of magnesium carbonate, the associated matrix sometimes contained as much as 30 per cent. of magnesium carbonate and less than 50 per cent. of calcium carbonate. He suggested that the concretionary structures resulted from a process of segregation and crystallisation of the calcium carbonate in a fossiliferous magnesian limestone, and was not due, as some have supposed, to the infiltration of calcareous water from overlying beds and its deposition in a porous stratum [7].

The Triassic System. — Although the Triassic rocks have hitherto been regarded as belonging to a separate geological system more recent than the Permian, Dr. Sherlock has, as already mentioned, adduced good reasons for regarding the Permian and Triassic rocks as representing different conditions of deposition during one great period of crustal unrest when arid and desert-like conditions generally prevailed. The Triassic rocks in this country consist mostly of marls, sandstones and conglomerates, resembling in many respects those included in the Permian System, and it is found that the higher beds spread out in all directions beyond the limits of the lower beds, indicating that the areas of deposition were increasing, probably because the land-locked basins in which the strata accumulated were being gradually filled up.

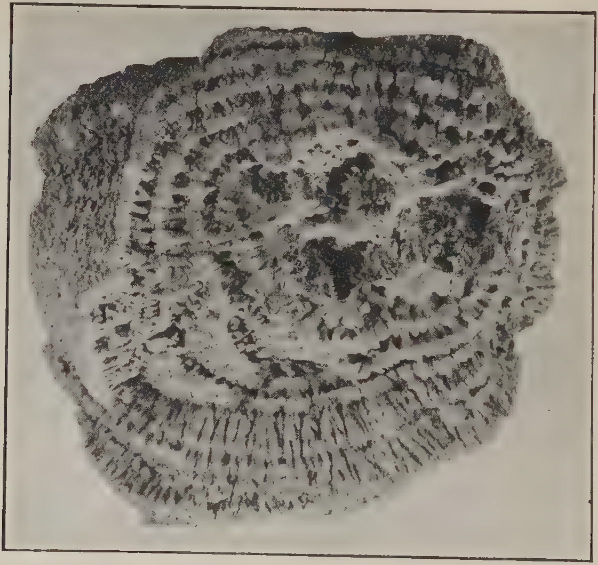

FIG. 86.—CONCRETION FROM THE MAGNESIAN LIMESTONE NEAR SUNDERLAND.

Specimen about nine inches in diameter, broken to show the internal structure. The arrangement of concentric layers and radial rod-like structures is such that the specimen appears to be of organic origin and resembles certain members of the Bryozoa, particularly *Theonoa,* which is found in the Crag Deposits of East Anglia.

The geographical conditions were similar to those already described in connection with the accumulation of the Permian rocks, and the Triassic rocks were evidently laid down upon the irregular surface of a continental region, gradually filling up the hollows until the original landscape was almost completely buried; *Fig.* 204. The extent to which the Palæozoic rocks were folded and denuded immediately before and during the deposition of the Trias is illustrated in *Fig.* 87, and it is interesting to note that in the south of Glamorgan denudation has now reached a stage when the elements of the pre-Triassic landscape are being again exposed [11].

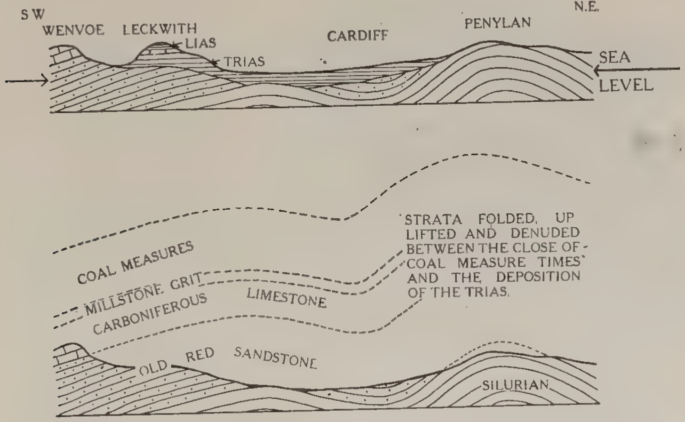
S W
N.E.
WENVOE
LECKWITH
LIAS
TRIAS
CARDIFF
PENYLAN
SEA
LEVEL
COAL MEASURES
MILLSTONE GRIT
CARBONIFEROUS
LIMESTONE
STRATA FOLDED, UP LIFTED AND DENUDED BETWEEN THE CLOSE OF COAL MEASURE TIMES AND THE DEPOSITION OF THE TRIAS.
OLD RED SANDSTONE
SILURIAN

FIG. 87.—SECTIONS ILLUSTRATING DENUDATION IN THE CARDIFF DISTRICT AT THE CLOSE OF COAL MEASURE TIMES.

After the deposition of the Coal Measures there ensued a period of earth movement during which the Palæozoic rocks were folded and extensively denuded (as the lower section indicates), before the rocks belonging to the Trias and the Lias were laid down. Later denudation has resulted in the removal of much of the covering of newer strata in South Wales, but, as the upper section indicates, they are still represented in parts of the area.

The existence of temporary salt lakes is indicated by the abundance of rock salt and of gypsum (*Fig.* 224) among the Triassic rocks of some localities, and the rounded condition of the grains in many of the sandstones indicates that the material was wind-borne. Evaporation was greater than the rainfall, and as the lakes gradually dried up the dissolved salts were deposited; having no protective covering of vegetation, the disintegrated rock material on the surface was readily disturbed by the wind, and in the form of dust and sand was blown about, covering the salt deposits, and covering also sun-cracked surfaces of mud (*Fig.* 88), the impressions of rain drops, and the footprints of reptiles that had walked on damp mud or sand by the side of the diminishing lakes or pools, so that everything points to the conclusion that the Trias must have been laid down under conditions similar to those in certain present-day arid continental regions — as for example, the country between Southern Palestine and the Caspian Sea.

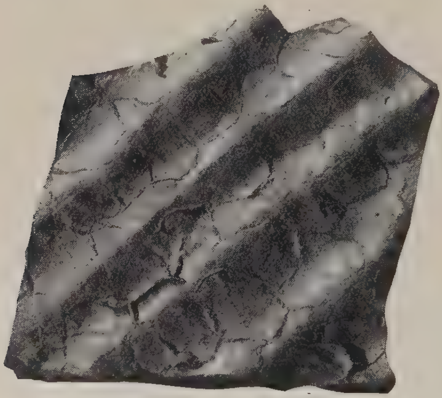

FIG. 88.—A ROCK SURFACE EXHIBITING RIPPLE MARKS AND SUNCRACKS.

Such a surface, in this case of a fine-grained calcareous sandstone in the White Lias of Glamorgan, indicates that the deposit must have accumulated in very shallow water, and after the retreating tide had made the ripples the surface dried and cracked, perhaps under the influence of a hot sun, before the water returned and deposited another layer of sandy mud, and the process was repeated; photograph about one-fourth natural size.

Such conditions are not favourable to the formation of limestone, which is practically absent from the Triassic rocks of this country. Here and there, where the denudation that accompanied the rock-folding that had been in progress since the close of Coal Measure times had resulted in the removal of all the later Carboniferous rocks and had exposed the Carboniferous Limestone, *that* rock formed the shores of the Triassic lakes, and in such localities the lowest beds of the Trias often consist of a conglomerate or breccia of Carboniferous Limestone pebbles cemented together by what was, at the time of its formation, a calcareous or dolomitic mud resulting from the disintegration of the limestone. The rock is sometimes known as the "Dolomitic Conglomerate."

Such limestone-conglomerate shore-deposits of Triassic age are seen, for example, at Barry in Glamorgan (*Figs.* 89 and 91) and in parts of the Mendip Hill country, but they are not usually sufficiently extensive or in other ways suitable to be of economic importance. An exception is the so-called "Draycot Marble" (*Fig.* 90) from the village of that name near Weston-super-Mare in Somerset; the rock, which consists of more or less angular fragments of Carboniferous Limestone in a pinkish matrix, takes a good polish and has been used for church decoration (steps and chancel pavements); a similar rock is quarried for building and constructional work at Ely, near Cardiff.

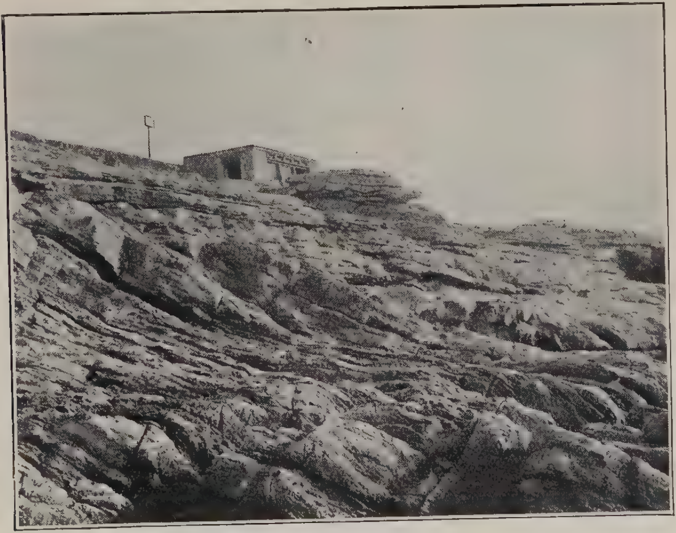

FIG. 89.—ANCIENT (TRIASSIC) BEACH DEPOSITS AT BARRY, GLAMORGAN.

Beach deposits formed during Triassic times rest horizontally upon a shelf cut by the waves into a cliff consisting of inclined beds of Carboniferous Limestone. (*Photo F.F.M.*)

The small but interesting occurrence of Trias in Western Mull (Scotland) includes beds known as "cornstones." They are sandy limestones composed largely of concretions and they have been compared with the modern "kankar" (or concretionary limestones) formed in certain parts of India and Africa, where an arid climate prevails during most of the year. Where the cornstones are comparatively pure, the rock might well be burnt locally for lime [10].

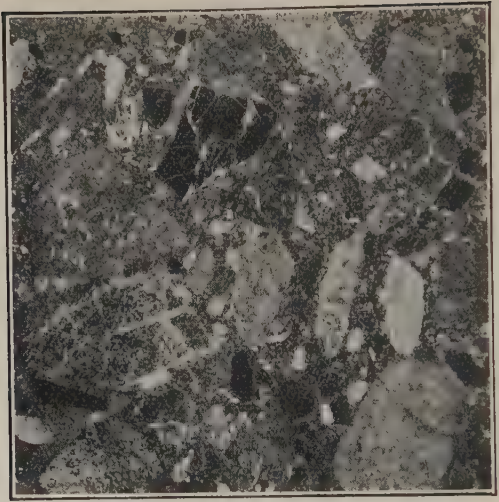

FIG. 90.—" DRAYCOT MARBLE."

A rock of Triassic age consisting of more or less angular fragments of Carboniferous Limestone set in a pinkish, calcareous (somewhat dolomitic) matrix; polished surface; about one-half natural size.

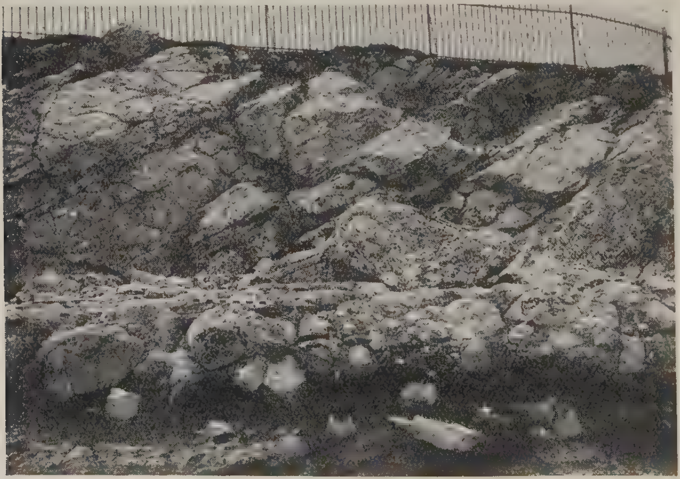

FIG. 91.—A " FOSSIL " PEBBLE BEACH.

An ancient beach of limestone fragments, now cemented together, and formed during Triassic times at the foot of a low cliff of Carboniferous Limestone. (*Photo F.F.M.*)

Although in the British area the Triassic rocks show a two-fold division into a *Keuper Series* above (consisting mostly of marls and fine grained sandstones), and a *Bunter Series* below (consisting of marls, sandstones coarser than those of the Keuper, and conglomerates), in Germany there is a three-fold division, because between the Bunter Series and the Keuper Series there is a thick limestone formation—the *Muschelkalk*, which, like the Magnesian Limestone of the English Permian is a somewhat abnormal type of marine limestone with an impoverished fauna. The open sea lay still farther to the south and east; there, typical marine and highly fossiliferous limestones were formed, including the vast deposits of dolomite that now, as a result of uplift and weathering, form the serrated peaks of the Dolomite Alps.

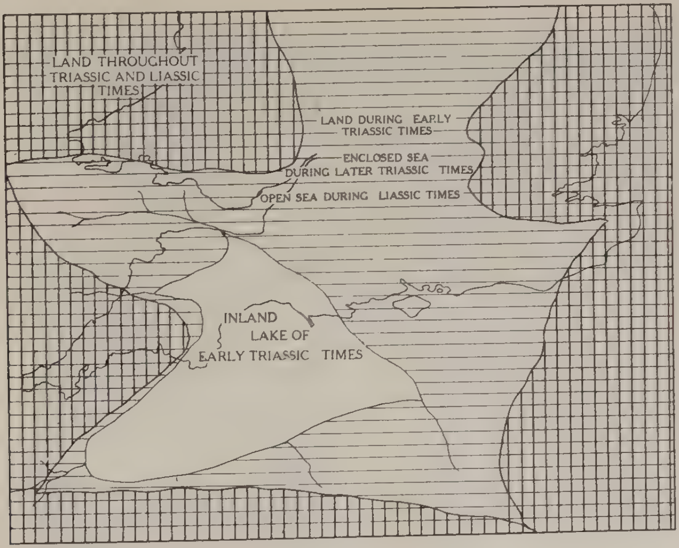
LAND THROUGHOUT TRIASSIC AND LIASSIC TIMES
LAND DURING EARLY TRIASSIC TIMES
ENCLOSED SEA DURING LATER TRIASSIC TIMES
OPEN SEA DURING LIASSIC TIMES
INLAND LAKE OF EARLY TRIASSIC TIMES

FIG. 92.—MAP ILLUSTRATING THE GEOGRAPHY OF PART OF ENGLAND AND WALES DURING THE EARLY PART OF THE MESOZOIC ERA.

In the south there was an inland (probably salt) sea during Triassic times, but before the close of Liassic times connection with the open sea had been established, and marine conditions prevailed over a considerable part of Great Britain. The region of the Bristol Channel was the estuary of a river draining from a western land mass.

The Rhætic Series.—The Rhætic Series has generally been regarded as the upper part of the Triassic System or as the lower part of the Jurassic, but there is a tendency on the part of continental geologists to regard it as belonging to a separate system. The name is derived from the Rhætian Alps in the Tyrol where the rocks are very well developed. In this country, although the Rhætic beds are only about 100 feet thick at their maximum development, they are of considerable interest because they represent the transition from the continental conditions of Permian and Triassic times to the marine conditions of the Lias.

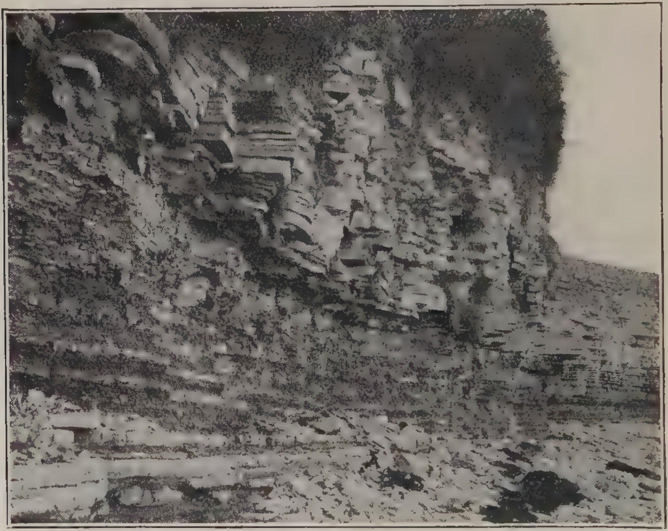

FIG. 93.—THE RHÆTIC BEDS AT PENARTH, GLAMORGAN.

The upper part of the cliff consists of the "White Lias" (mainly limestones, which include the horizon of the Cotham Marble); the middle part, which, consisting of soft rock, is removed more rapidly, and gives rise to "undercutting," comprises the "Black Shales"; and the lowest part consists of the hard grey marls that are transitional between the Triassic deposits and those of Rhætic age. (*Photo F.F.M.*)

By the time the earth-movements that were responsible for the desert and inland salt lakes of Permian and Triassic times had died out, the post Carboniferous deposits had more or less completely buried the desert landscape, and at the end of Keuper times a great shallow lake seems to have covered much of the British area, while the open sea lay to the south-south-east (*Fig.* 92).

Either because of local subsidence, or because of the removal of the barrier that had kept back its waters, the sea returned to the British area bringing with it many molluscs and fishes, as well as marine reptiles that in other regions had been evolving from the amphibian vertebrates that had lived in the waters of the Coal Measure swamps. The return of the sea appears to have been rapid, and the animals thus brought into the stagnant waters of the Keuper lake were to a large extent killed off, with the result that the lower part of the Rhætic Series is in many places characterised by a " bone bed " consisting largely of rolled fragments of the bones and teeth of reptiles and fishes. Most of the molluscs survived the change in their surroundings, and lived on in a stunted condition.

The influx from the ocean continued and diluted the water of the excessively salt lakes until ordinary marine life was able to establish itself over the whole of the area then occupied by the sea, and the Liassic rocks, which constitute the lowest division of the Jurassic System, began to accumulate. It is the group of beds formed during the period of transition that constitutes the Rhætic Series. Although present in other parts of the country, the Rhætic rocks are best developed in the south-west of England (in Somerset) and in Glamorgan; the most important section occurs at Penarth, near Cardiff—the strata were originally known as the *Penarth Beds* (see *Fig.* 93).

In the Bristol Channel region the Rhætic Series includes :—

The White Lias—marls and limestones including the *Cotham Limestone*,

Black Shales—(*Westbury Beds*) with a " Bone Bed " at or near the base,

Grey Marls—(*Sully Beds*),

and a similar succession is seen on the Dorsetshire coast near Lyme Regis. In the Midlands the Series is thinner (only about 40 feet) and it includes blue shales with very thin limestones above, and black shales below. An interesting feature of the Rhætic Beds in Glamorgan is that when traced westwards from Penarth they undergo a remarkable lithological change and pass into greenish and yellow sandstones, indicating the proximity of the shore of the sea in which they were deposited; this matter will be discussed more fully in connection with the Liassic strata of South Wales.

Although of considerable scientific interest the Rhætic Limestones are not of present economic importance; those of the White Lias were formerly burnt for lime, and they have been quarried for rough building near Castle Cary, Somersetshire, while a rock of similar age at Chesterton Quarry near Warwick has been used for internal carved work because it can be cut with considerable precision.

Cotham Marble.—In the marls near the base of the "White Lias" there are a few hard compact limestones occurring as nodules or as impersistent beds; they are found at various places between Bristol and Uplyme in Devonshire. Where the limestone occurs as a persistent layer it is more or less evenly bedded, but in the case of the nodular masses (which are from a few inches to three feet across), although the lower surfaces are fairly even, the upper surfaces are peculiarly crinkled and corrugated and bear some resemblance to a cauliflower. The crumpled surfaces appear to be due to shrinkage of the original calcareous mud from which the nodules were formed, and they are usually accompanied by an arrangement of arborescent or tree-like markings within the body of the stone (*Fig.* 94).

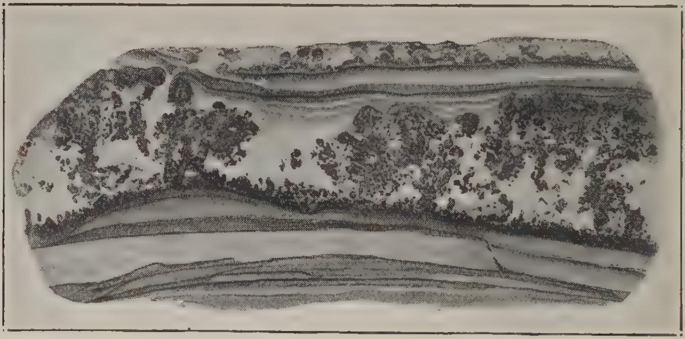

FIG. 94.—LANDSCAPE MARBLE.

A rock that occurs as nodules in beds of Rhætic age; also called Cotham Stone from the place of that name near Bristol; about half natural size.

The ground-mass is light grey or fawn in colour, while the tree-like markings are much darker. On surfaces cut at right angles to the bedding, the "trees" are seen to rise from more or less horizontally arranged layers near the base of the nodule, and the general appearance is that of a landscape, the main feature of which is a series of trees, with bushes between them, clouds above, and level fields and even water in the foreground. This character has given rise to the name *Landscape Marble*, and the stone is also called *Cotham Marble* from a locality near Bristol where it is well displayed. Sometimes there are two " landscape " layers, one above another, in the same nodule.

Attention was first drawn to the stone and the name Cotham Marble applied to it by Edward Owen, in *" Observations on the Earths, Rocks, Stones, and Minerals, for some miles about Bristol, and on the Nature of the Hot-Well, and the Virtues of its Water,"* 1754. He suggested that the tree-like markings were produced by the escape of imprisoned air, that, as it made its way to the surface, disturbed the layers of the soft mud, from the consolidation of which the nodules resulted.

Various other suggestions have been made to account for the " landscape " structure. In 1892, H. B. Woodward described the occurrence and distribution of the rock. He pointed out that wherever it occurs, the Cotham Stone occupies a position between dark argillaceous or shaly sediments below and nearly pure calcareous muds above, and that it represents special conditions of deposition when the calcareous mud was to some extent contaminated by films of the argillaceous material. Sometimes the result was an ordinary banded argillaceous limestone such as occurs in many places at the stratigraphical position of the Cotham Stone, and sometimes the " landscape " structures were developed. Woodward explained the latter by supposing that during the consolidation and subsequent shrinkage of the calcareous muds, some of the thin dark argillaceous films interbedded with them were disarranged and dispersed [8].*

In 1894, Beeby Thompson revived Edward Owen's " gaseous emanation " theory in a modified form, and maintained that the arborescent structures are due to the fact that there were interbedded layers of vegetable matter, the decomposition of which gave rise to gases such as carbonic acid gas and marsh gas. He supposed that the " landscapes " were due to the disturbance of the mud during the escape of the bubbles of gas, and described experiments made to reproduce the characters of the stone [9].

Cotham stone has been used for making paper weights and small ornaments, and occasionally for internal decoration, but it has not the economic importance that the abundance of specimens in museum collections might suggest.

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* See Additional Note, page 447.

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CHAPTER IX.

LIMESTONE IN THE JURASSIC SYSTEM: THE LIAS.

"This let me further add, that Nature knows
No stedfast station; but, or ebbs or flows;
Ever in motion, she destroys her old,
And casts new figures in another mould.
. . . .
And ev'ry moment alters what is done
And innovates some act till then unknown."
Ovid, *Metamorphoses* XV., Dryden's translation.

The Jurassic System.—The return of the sea referred to in connection with the formation of the Rhætic deposits, inaugurated a long marine period in the region with which we are concerned, for nearly all the British rocks of the Jurassic System are of marine origin; the exceptions are some beds near the middle of the System, which are estuarine, and others at the top, which accumulated in fresh water.

The name "Jurassic" is derived from the Jura Mountains, N.E. of the Alps, where the rocks are well developed, but some of them were called "Oolitic" by William Smith on account of the frequent development of oolitic structure in the limestones and ironstones (*Figs.* 26 and 95).

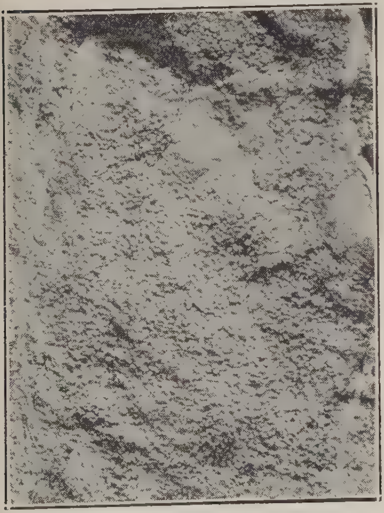


FIG. 95.—Oolite.
Oolitic structure in ironstone of Corallian age, Westbury, Wilts; about natural size.

Rocks belonging to the Jurassic System occupy the south coast between Weymouth and Lyme Regis, and their outcrop extends across the country in a generally north-easterly direction;

it is the widest in the latitude of Rugby and Huntingdon, becomes very narrow in the South of Yorkshire, and disappears north of Market Drayton, because the chalk "oversteps" the Jurassic rocks and rests directly on the Trias. In the North of Yorkshire

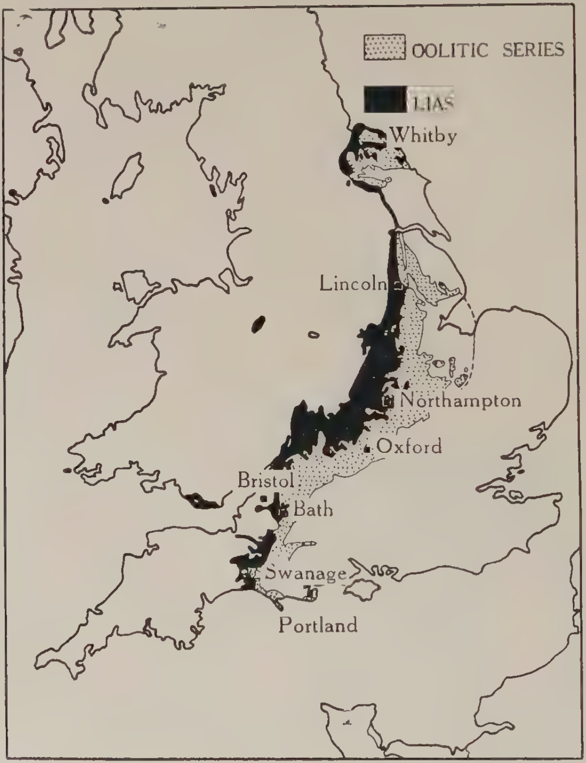

OOLITIC SERIES
LIAS
Whitby
Lincoln
Northampton
Oxford
Bristol
Bath
Swanage
Portland

FIG. 96.—THE OUTCROPS OF THE LIAS AND THE OOLITES IN ENGLAND AND WALES.

(In the Fen country the outcrop of the Oolites is concealed by alluvial material.)

the outcrop is a large diamond-shaped area, including the Cleveland Hills, and it ends at the coast between Redcar and Filey; *Fig.* 96.

Taken as a whole, the Jurassic deposits are mainly clays (or shales) and limestones, although sands, sandstones, and some important ironstones are also present: the principal sub-divisions are indicated in the table constituting *Fig.* 97.

The limestones form prominent escarpments (such as the Cotteswold Hills) and the clays give rise to low-lying but generally fertile vales, in which occur the richest dairy farming areas of the country, although the soils that are directly derived from clays like the Oxford clay are cold and heavy.

THE JURASSIC SYSTEM.

Upper Oolites		Purbeck Beds—clays and *limestones* (freshwater).
		Portland Beds—*limestones* and sands
		Kimmeridge Clay—clays and shales.
Middle Oolites		Corallian Beds—mainly *limestones* and grits.
		Oxfordian Beds—clays and sands.
Lower Oolites	Great Oolite Series	Cornbrash—earthy *limestones*.
		Forest Marble—*limestone* and clay.
		Bradford Clay.
		Great Oolite—*oolitic and shelly limestones*.
		Fuller's Earth—clay.
	Inferior Oolite Series	Inferior Oolite—*oolitic and shelly limestones*.
		Midford Sands (part)—sands.
Lias		Upper Lias—clays, shales and sands.
		Middle Lias—clays, ironstones, and *limestones*.
		Lower Lias—clays, shales and *limestones*.

FIG. 97.—CLASSIFICATION OF THE JURASSIC ROCKS.

This classification is based on the succession in the west and south of England; in Yorkshire the Lower Oolites include sandstones and shales of estuarine origin.

The clay divisions (Lias, Oxford Clay, and Kimmeridge Clay) maintain their argillaceous character more or less throughout the whole length of the outcrop, but the calcareous divisions tend to become sandy or argillaceous as they are traced from south to north. The uppermost strata—the Portland Beds and Purbeck Beds—are of more limited extent than those below, and are practically confined to the south of England.

On the east and south the rocks pass beneath newer strata, and they have been met with in numerous borings in the eastern and southern counties, but the western extremity of the outcrop is determined by denudation, and the Jurassic strata formerly extended much further in that direction than they do at the present time (*Fig.* 98); this is indicated by the existence of outliers of Lias on the Cheshire borders, near Carlisle, and in Northern Ireland, and by outliers of various divisions of the Oolites in the Inner Hebrides and in Sutherlandshire (*Fig.* 131).

The life of the Jurassic Period. — The plants were very different from those of the Coal Measure forests, and, as would be expected, were more closely related to modern types: cycads (palm-like plants), conifers (pines and firs), and ferns were abundant. Fossil plants are most abundant in the estuarine and freshwater beds.

As far as its vertebrate life is concerned, the Jurassic Period (together with the earlier part of the succeeding Cretaceous Period) is essentially the "*Age of Reptiles*," for reptiles were the dominant animals on the land, in the air, and in the water, but, like the plants, they did not contribute to the formation of limestone, and do not call for comment here [1-3]. Mammals and birds also made their appearance during the Jurassic period, but they did not become important until after its close.

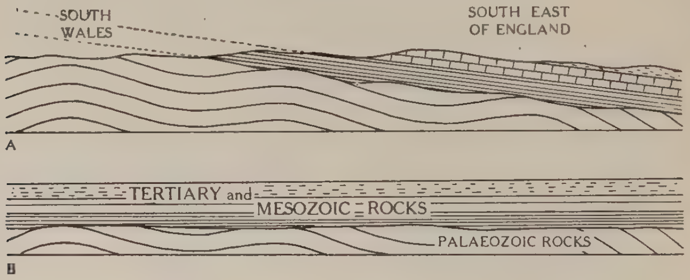


FIG. 98.—Diagram illustrating the former extension of Mesozoic and later deposits in South Wales.

Although at the present time the Mesozoic and Tertiary rocks have a general dip to the south and east and (as shown by Section A) do not extend into South Wales (except for the occurrence of Lias in Glamorgan) they were originally laid down as more or less horizontal beds, and extended farther to the west as indicated in Section B. The present condition is the result of unequal uplift and denudation (see also Fig. 15). It should be noted that the sections are diagrammatic and intended to illustrate general principles only: it is not likely that the whole of the Mesozoic and Tertiary strata as now represented in the east were deposited in the west.

Marine invertebrates were exceedingly varied and abundant, for corals, sea-urchins, star-fishes, brachiopods, and molluscs all contributed largely to the formation of thick and extensive deposits of limestone. Among the molluscs, the cephalopods were perhaps the most prominent; they include the belemnites (*Fig.* 136), whose pointed cylindrical "guards" are sometimes locally known as thunderbolts, and the coiled ammonites, which were so numerous and varied that the period has sometimes been called the Age of Ammonites (*Fig.* 99).

Geography of the Jurassic Period.—The time involved is so great, and the geographical conditions varied so much, that, as in the case of earlier periods, it is only possible in this brief account to indicate in a general way the mode of accumulation of the Jurassic strata [4, 5].

The Liassic strata were laid down in a sea that was more or less similar in character to, although slightly larger than, that which resulted from the incursion of the sea (during Rhætic times) into the inland lake in which the later Keuper deposits had accumulated. The water, probably at no time very deep, was often quite shallow, and with its abundant fauna, including large reptiles such as *Ichthyosaurus* and *Plesiosaurus* (*Figs.* 100-101), fishes, molluscs, lobster-like crustaceans, and colonies of crinoids and sea-lilies, the Liassic sea must have contrasted strongly with the almost lifeless stagnant waters of most of the Permo-Triassic inland seas.

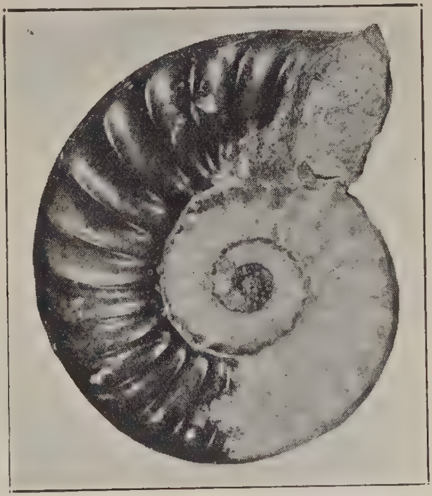


FIG. 99.—AN AMMONITE.

Asteroceras obtusum from the Lower Lias of Charmouth, Dorset; slightly reduced.

During the earlier part of Oolitic times there were earth movements that resulted in the sea being subdivided into a number of more or less clearly defined basins, and although these often intercommunicated, the conditions were sufficiently varied to permit the accumulation of different kinds of deposits in the various basins. Most of the limestone accumulated in clear water, and that the water was generally shallow is indicated by the abundant development of oolitic structure (the origin of which will be discussed at a later stage), and by the frequency with which the

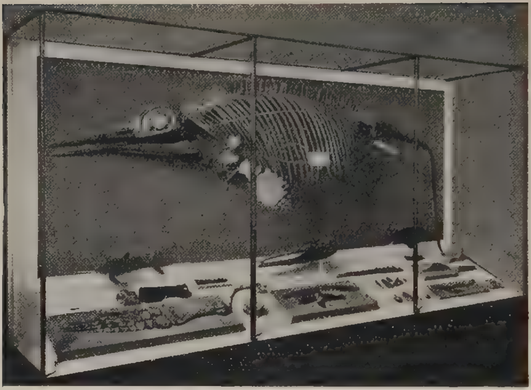


FIG. 100.—BONES OF JURASSIC MARINE REPTILES, belonging to the *Ichthyosaurus* group; in the National Museum of Wales.

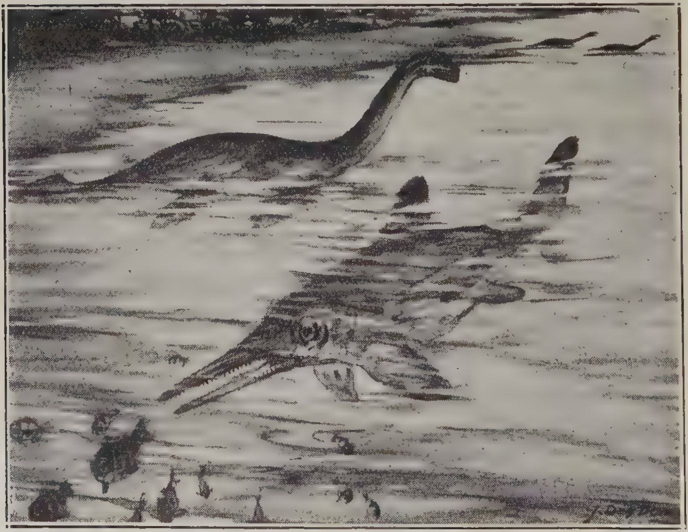


FIG. 101.—*Plesiosaurus* (above) and *Ichthyosaurus* (below). Sketch illustrating the probable appearance in life of two of the marine reptiles of the Jurassic period.

sands and even the limestones show evidence of current action (false bedding). The earth movements were, in general, slight, but they resulted in the local uplift of certain regions for sufficiently long to allow some of the newly accumulated deposits to be removed by denudation, giving rise to small unconformities or non-sequences; see page 17. On this account, not only are the difficulties of correlating the strata greatly increased, but the time represented by the Jurassic rocks—the Jurassic Period—is considerably longer than their total thickness would lead one to suppose; see *Fig.* 102.

In some places, large, swampy, tree-clad areas were developed, and in such regions plant-bearing muds were deposited, under estuarine conditions recalling those of Coal Measure times; it was in such a region that the estuarine beds in the Lower Oolites of Yorkshire accumulated. Towards the end of Lower Oolitic times, when the thin earthy limestones of the Cornbrash were laid down, marine conditions prevailed over practically the whole country, and the Cornbrash is, for a Jurassic deposit, remarkably uniform throughout the whole extent of its outcrop.

The lower part of the Oxfordian Beds (the Kellaways Rock, named from Kellaways in Wiltshire) accumulated in a sea similar to that of Cornbrash times, and under conditions which were very favourable to molluscan life, ammonites in particular being abundant; but a great change commenced early in Middle Oolite times — the sea became very muddy over the whole of the British area, and, except locally in the south, where the Corallian Beds are calcareous and rich in corals

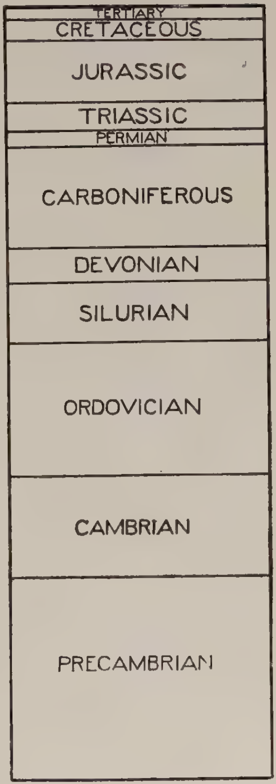


FIG. 102.—TABLE OF STRATA,

showing relative thickness of the rocks of the various Geological Systems; as explained above the length of the period of time which each System represents is not always proportional to the thickness of the rock included in it.

indicating a clear sea, it remained so for a long time during which the Oxford Clay and the Kimmeridge Clay accumulated.

The record of the rocks shows that long periods, during which marine deposits accumulated (indicating a movement that is in general one of subsidence) have always been followed by periods of uplift, and often by the development of continental conditions; and this was the case during Jurassic times, for after the accumulation of the Kimmeridge Clay, a ridge was formed, extending across England in a generally east to west direction and separating a northern from a southern area of deposition.

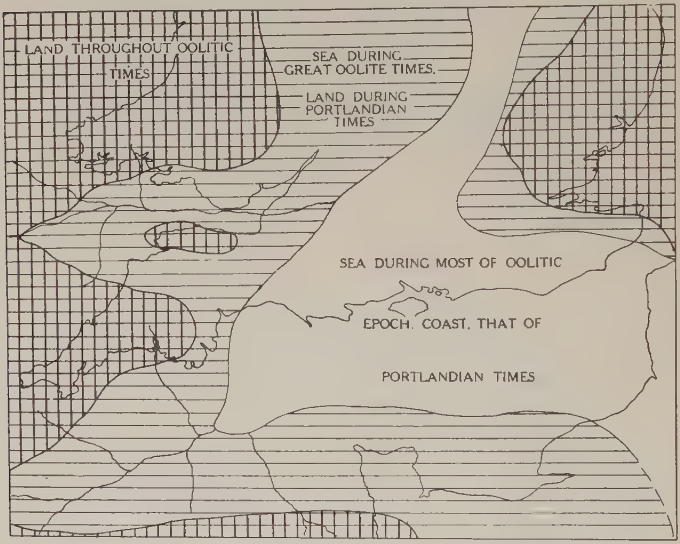

LAND THROUGHOUT OOLITIC TIMES
SEA DURING GREAT OOLITE TIMES.
LAND DURING PORTLANDIAN TIMES
SEA DURING MOST OF OOLITIC EPOCH. COAST. THAT OF PORTLANDIAN TIMES

FIG. 103.—MAP ILLUSTRATING THE GEOGRAPHY OF PART OF ENGLAND AND WALES DURING THE JURASSIC PERIOD.

The shores of the sea in which the Jurassic rocks accumulated were constantly shifting, but as the period drew to a close the area occupied by water became steadily less.

In the south of England, marine conditions continued while the Portland limestones and sands were laid down (*Fig.* 103), but the change which has been taken as indicating the close of the Jurassic Period was commencing, because the succeeding Purbeck Beds are in part estuarine and in part of freshwater origin; they even include certain " dirt beds " which are the remains of plant-bearing soils indicating periods during which dry land conditions prevailed.

No Portland beds are now present in the north; they may have been deposited, but if so they were very soon afterwards removed by denudation. The sea returned to the northern region while the Purbeck Beds were accumulating in the south, for marine clays (*Speeton Clay*) and sandstones (*Spilsby Sandstone*), which occur in Yorkshire and Lincolnshire, form the topmost Jurassic Beds, and are transitional to those belonging to the succeeding Cretaceous Period.

Although in some measure a repetition of the conditions of Carboniferous times—a long marine period, followed by one during which shallow-water swampy conditions prevailed, and eventually by a continental period—the conditions at the close of Jurassic times differed from those of Permian and Triassic times in that there were no deserts or extensive inland salt seas; the country was, in general, low lying, damp, and well-covered with vegetation, and it supported an interesting reptilian fauna, including members of the Dinosauria.

Dry conditions probably occurred locally towards the end of the period, because apart from the evidence of old land surfaces in the Purbeck Beds, the rocks of this age near Battle in Sussex include shales with gypsum, and the water they yield is somewhat saline [6].

Limestones in the Jurassic System.—The principal limestones, which are as follows, will be referred to briefly in order, commencing with the lowest (and oldest) of the series.

Purbeck Limestones, *Purbeck Marble* and *Swanage Stone.*

Portland Stone, including *Seacombe Stone, Chilmark Stone,* and *Tisbury Stone.*

Corallian Limestones, for example, *Osmington Stone, Calne Stone, Headington Stone,* and *Wheatley Stone.*

Great Oolite Limestones, for example, limestones in the Cornbrash, *Forest Marble, Bath Stone, Farley* (*Farleigh*) *Down Stone, Corsham Down Stone, Box Ground* or *St. Aldhelm Stone, Coombe Down Stone, Bradford Stone, Taynton Stone,* and *Denton Stone.*

Inferior Oolite Limestones, for example, *Dundry Hill Stone, Ham Hill Stone, Doulting Stone, Painswick Stone, Weldon Stone, Bourton Stone, Ketton Stone, Barnack Stone, Ancaster Stone,* and *Haydor Stone.*

Lias Limestones, including *Hornton Stone* and *Sutton Stone.*

Limestones in the Lias.—Except in its lowest part, the Lias is mainly a clay formation: in the south, however, the Lower Lias comprises alternations of shale and limestone, in which the limestones are sufficiently abundant to be of economic importance.

The limestone-shale alternation is very well displayed in the wall-like cliffs of Glamorgan, as, for example, at Lavernock and between Rhoose and Dunraven (*Figs.* 2, 104, and 105); it is also to be seen in railway cuttings in the Vale of Glamorgan and is present in parts of Somersetshire and in Northamptonshire.

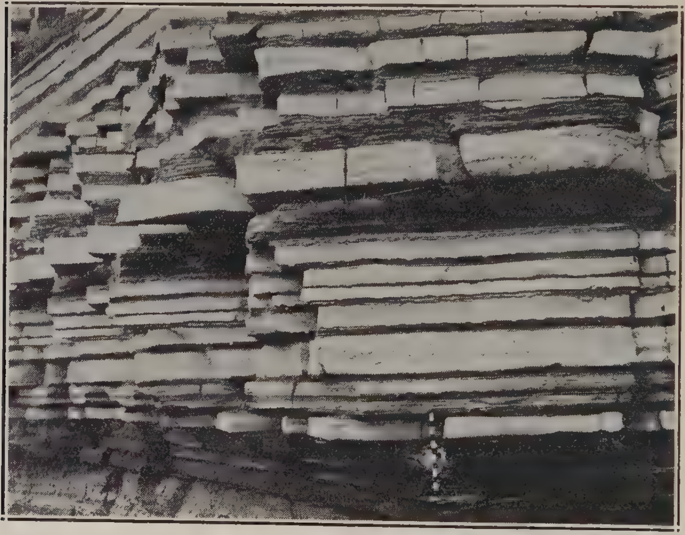


FIG. 104.—CLIFF AT LAVERNOCK, NEAR CARDIFF.

The strata belong to the Lower Lias and consist of limestones alternating with dark shales: the cliff section shows stratification and well developed joints. The ruler is one foot long.

(*Photo F.F.M.*)

The limestones are thinly bedded, and, although separated by beds of shale and affected by joints so that blocks are easily detached, they do not as a rule make good building stones, because, for the most part, the rock yields readily to the weather and tends to split under the influence of frost.

Most of the Lower Liassic Limestones are bluish grey or slate-coloured, and buildings in which they are used are of sombre appearance; exceptions to this are seen in the Sutton Stone of Glamorgan, shortly to be described, and in the light coloured rock from Wilmcote in Warwickshire, used in the interior paving of the Houses of Parliament and the Law Courts.

For building purposes the ordinary argillaceous limestone has been used more in the past than at the present, and there is a tendency for it to be replaced as a building medium by bricks made from the associated clays. Examples of its former use are to be seen in Worcestershire, Warwickshire, Glamorgan and Somerset (*e.g.*, the town of Street, and certain of the early ecclesiastical buildings at Glastonbury): it is, however, often used for paving-slabs and kerbs, and is still quarried for building purposes near Shepton Mallet.

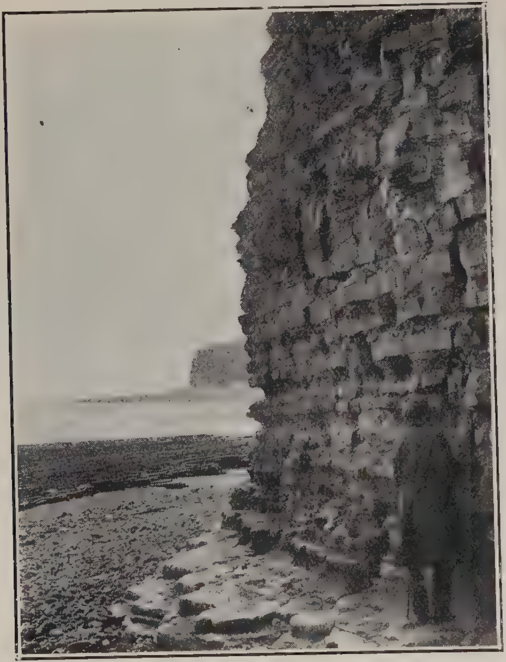


FIG. 105.—CLIFFS OF LIAS LIMESTONE.

The Lower Lias, comprising alternations of thinly bedded limestone and shale, near Porthkerry, Glamorgan. (*Photo W.E.H.*)

Of considerable interest, although of no present importance, is the so-called *Marston Marble* of Marston Magna, near Yeovil. This is a limestone in the Lower Liassic series consisting almost entirely of the shells of various species of ammonites, and at one time it was cut and polished for table tops and small ornamental objects. The supply was limited and none has been obtained for many years. The rock appears to have been first discovered about the middle of the eighteenth century and there was a specimen in the Collection of Sir Hans Sloane—which collection, it may be remembered, became the nucleus of what is now the British Museum; a similar rock has been recorded from Ilminster and from Lyme Regis.

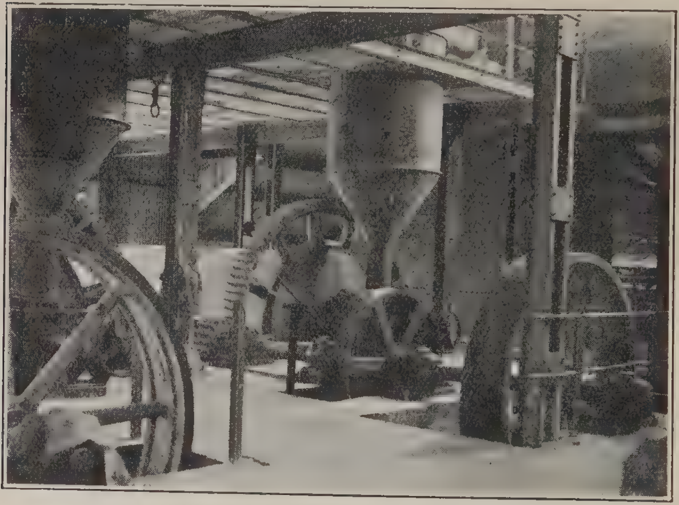


FIG. 106.—MILLS FOR GRINDING CEMENT.

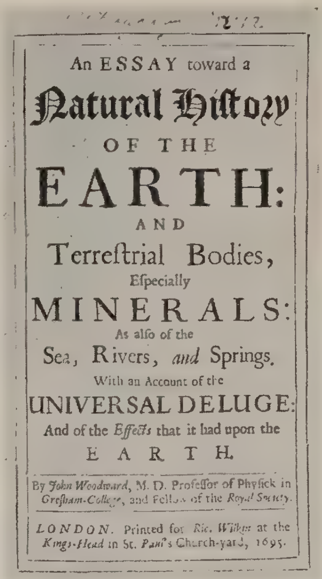
These consist of large cylinders charged with rounded nodules of flint "Greenland pebbles," the movement of which, as the cylinders rotate, effects the grinding of the clinker.

A shelly limestone about one foot in thickness and known as *Banbury Marble*, from its occurrence near that town, was formerly used locally for mantelpieces.

The Lower Lias limestones are extensively used for lime burning and for cement making in most districts where they occur.

The use of the Leicestershire rock for lime burning was recorded as far back as 1729 by John Woodward* in his "*Natural History of the Fossils of England*" (Vol. 1, p. 26), where he spoke of ammonites being found "in a quarry the most famous in England for Limestone; it being very hard and making an excellent lime, at Barrow in Leicestershire."

The value of the limestone in cement making lies principally in the fact that, with the associated shales, the limestones, which are themselves argillaceous, yield a mixture that contains calcium carbonate and aluminium silicate in nearly the correct proportions to yield a perfect cement when suitably burnt and ground (*Fig.* 106); if necessary the proportion of calcium carbonate is increased by the addition of the purer Carboniferous Limestone; see also p. 400. The cement-making value of the Liassic Limestone of South Wales has long been known; when John Smeaton, the builder of the third Eddystone Lighthouse, was seeking stone for hydraulic cement, he found the rock at Aberthaw admirably suited for the purpose, and, desirous of obtaining similar stone elsewhere, he traced the outcrop of the Lias from the Glamorgan coast through Monmouthshire into Nottinghamshire, and he also referred to its occurrence in the north of Somerset and at Lyme Regis. Apart from George Owen's survey of the Car-



An ESSAY toward a
Natural Hiſtory
OF THE
EARTH:
AND
Terreſtrial Bodies,
Eſpecially
MINERALS:
As alſo of the
Sea, Rivers, *and* Springs.
With an Account of the
UNIVERSAL DELUGE:
And of the *Effects* that it had upon the
EARTH.

By *John Woodward*, M. D. Profeſſor of Phyſick in
Greſham-College, and Fellow of the *Royal Society*.

LONDON. Printed for *Ric. Wilkin* at the
Kings-Head in St. *Paul's* Church-yard, 1695.

FIG. 107.—THE TITLE PAGE OF JOHN WOODWARD'S "NATURAL HISTORY OF THE EARTH" (1695).

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* John Woodward was something of a character in his time. He was one of the first in this country to make a systematic collection of geological specimens and, by bequest, founded what is now the Woodwardian Chair of Geology at Cambridge. The collection was described in his "*Natural History of the Fossils of England*," but he is perhaps better known for a remarkable work "*An Essay towards a Natural History of the Earth*" (1695), the title page of which is illustrated in Fig. 107. In it he argued that the present arrangement of the earth's surface, the distribution of its rocks, and the entombment of the fossils they contain, are all to be attributed to the effects of one Universal Deluge [see 20 & 21].

boniferous Limestone mentioned on a previous page, this was one of the earliest attempts to trace across the country the outcrop of a set of strata, and it is referred to by Smeaton in his book on the building of the Lighthouse (1791) [7]. As de la Beche pointed out in his "*Report on the Geology of Cornwall, Devon, and West Somerset*" (1839), however, Smeaton could have obtained material just as suitable for his purpose at Lyme Regis, without taking it all the way from the Bristol Channel, *i.e.*, from Watchet.

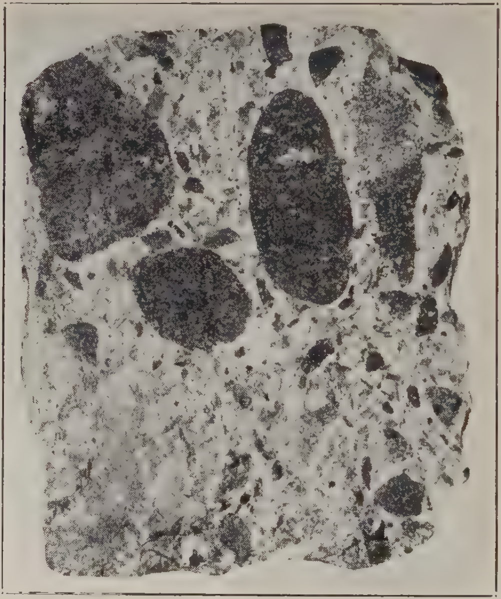

FIG. 108.—SUTTON STONE.

Limestone of Lower Liassic age (from Sutton in Glamorgan) consisting of pebbles of Carboniferous Limestone in a matrix of limestone debris; about natural size.

The Liassic Limestones do not make good roadstones, for, being comparatively soft, they tend to powder readily, giving rise to much dust in dry weather and to sticky mud in wet weather.

Sutton Stone.—The Sutton Stone, which occurs at Sutton near Bridgend, is an interesting local variety of the Lower Lias limestone. It is a pale creamy rock, of which some varieties are compact like freestone, others are almost as porous as calcareous tufa, and others are conglomeratic (*Fig.* 108). It was extensively used in the ecclesiastical buildings of Norman times in Glamorgan, and may be seen in Llandaff Cathedral and Neath Abbey.

The Sutton Stone owes its peculiar characters to the fact that it was deposited near the shore of the Liassic Sea, where the cliffs consisted of Carboniferous Limestone; *Fig* 109. In the more open water the Lower Lias deposits were alternations of limestone and shale, but the ancient shore line lay near Southerndown, and there, the Lias resulted from the destruction of, and was deposited upon, the Carboniferous Limestone, and the rock is, to a large extent, composed of Carboniferous Limestone debris, in fragments varying in size from pebbles down to calcareous mud. The original sedimentary matter has been extensively recrystallised, and in places the rock now consists principally of crystalline calcite; to this is due its value as a building stone.

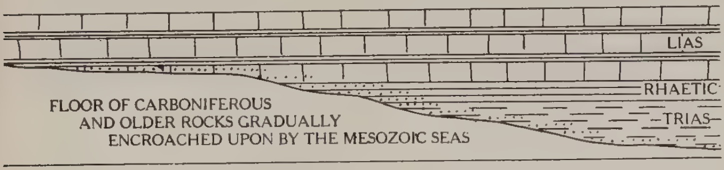
LIAS
RHAETIC
TRIAS
FLOOR OF CARBONIFEROUS AND OLDER ROCKS GRADUALLY ENCROACHED UPON BY THE MESOZOIC SEAS

FIG. 109.—DIAGRAMMATIC SECTION ILLUSTRATING CHANGES IN THE TRIASSIC AND LIASSIC DEPOSITS FROM EAST TO WEST IN GLAMORGAN.

As the sea encroached upon the old land surface of Carboniferous rocks, beach deposits were formed—represented in the section by dots—so that the lowest beds of the Trias in the east of Glamorgan and of the Lias in the west, consist of rocks of peculiar shallow-water types.

Rocks similar to the Sutton Stone occur in some localities in Somerset where the Lias represents a shore deposit and rests on Carboniferous Limestone; they are quarried near Shepton Mallet and near Wrington, but the Brockley Down Stone of the latter locality is more porous than the Sutton Stone.

Resting on the Sutton Beds in Glamorgan are the *Southerndown Beds*, which are dark blue limestones with thin shale bands; these limestones, too, contain fragments of Carboniferous Limestone, but they are not of economic importance.

Although the Liassic Sea spread westwards at least as far as Sutton and Southerndown, it does not appear to have extended far in the direction of the coalfield region of South Wales, for at St.

Fagans, which is north of the main Vale of Glamorgan Liassic mass, the rock is largely a massive oolite of shallow water origin. (It is on evidence such as this that the geography of past geological periods is reconstructed.) A somewhat exceptional mode of occurrence of oolitic grains has been noted in certain clays of shallow water origin in the Liassic series: for example, approximately one twentieth of the mass of a bed of clay, about 12 inches thick, near Grantham, was found to consist of oolitic grains with the typical arrangement of concentric layers of calcite [23a]. In many of them were traces of minute tubules, like those ascribed to the activity of the alga *Girvanella,* to which further reference is made in the next chapter.

The somewhat peculiar nature of the Lower Lias—thin beds of strong hard limestone alternating with shales—and the fact that the beds usually lie flat or are only gently inclined, has sometimes led to the development of "quarries" very different in type from the large excavations to which that name is usually applied. At Barnstone, near Nottingham, for example, where the beds lie quite horizontally, the rock is excavated for cement making [23b]. The limestone occurs in beds from 6 to 12 inches in thickness and there are the usual intercalations of shale, very little of which is required for the manufacturing process. There is no steep quarry face in the ordinary sense; each bed of limestone is stripped away after the "overburden" of soil and weathered material

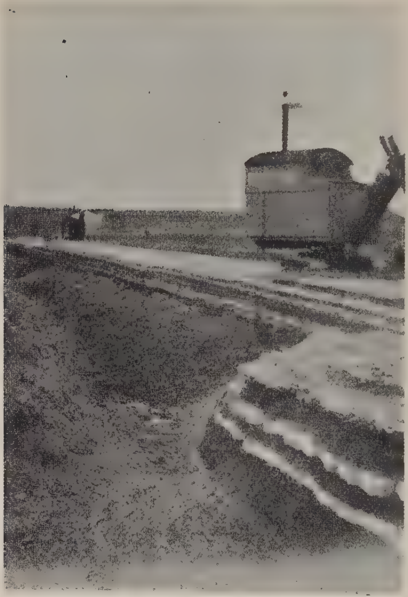

FIG. 110.—A QUARRY IN LIASSIC LIMESTONE.

Limestones alternating with shales lie horizontally and are removed bed by bed, the unwanted shale being dumped in the area from which the limestone has been removed; by courtesy of the Barnstone Cement Company, Ltd.

has been removed, and the shale beneath it, apart from the small proportion that is wanted, is dumped into the excavation behind, so that as the "working face" moves slowly along, the area from which the limestone has been removed is practically flat but at a somewhat lower level than before; see *Fig.* 110.

Nodular and concretionary limestones.—The limestones of the Lower Lias often exhibit peculiar characters that suggest unusual conditions of formation. Some of the beds have smooth surfaces, as may be seen where they are displayed on the foreshore near Penarth in Glamorgan (*Fig.* 111), while in others the surface is hummocky and the bed has the appearance of being made up of nodules that have grown until they met (*Fig.* 112), recalling the nodular limestones present in parts of the Wenlock Limestone series. The close association of flat and nodular beds is seen in the cliff-section illustrated in *Fig.* 113.

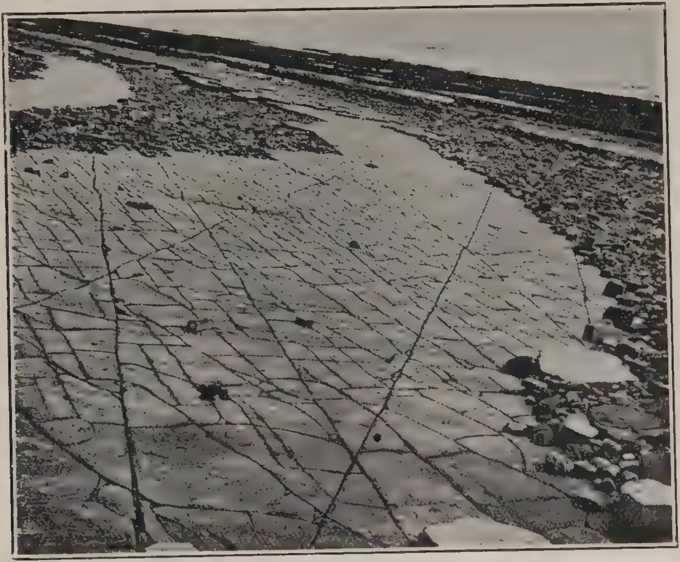

FIG. 111.—JOINTS IN LIMESTONE.

The surface of a bed of limestone in the Lower Lias, exposed on the foreshore near Penarth, Glamorgan, showing the regularly arranged (and in this case rather densely packed) joints.

(*Photo F.F.M.*)

The nodular character of so many of the beds suggests that the series of limestones and shales making up the Lower Lias of many areas is not a normal alternation of calcareous and argillaceous deposits, and that the present distribution of calcium carbonate has been determined by processes other than ordinary sedimentary deposition.

The matter has been discussed by numerous writers, and various suggestions have been made to account for the phenomenon [8-12], but it seems to be probable that the deposit was originally a mass of clay highly charged with calcium carbonate (derived from the denudation of the Carboniferous Limestone and the Upper Carboniferous shales) and that when the deposits were first elevated into the condition of dry land, the draining away and drying up of the water resulted in the redistribution of the calcareous material, which was deposited rhythmically according to the laws governing the deposition of salts diffusing through colloidal* media—the colloid in this case

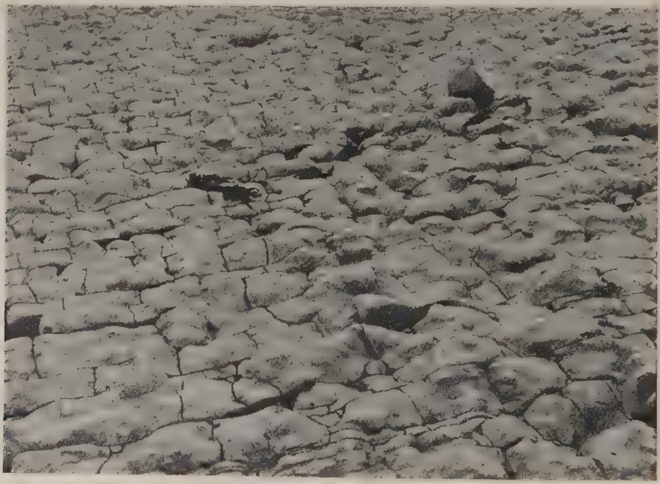

FIG. 112.—NODULAR LIMESTONE IN THE LIASSIC FORMATION.

The surface of a bed of nodular limestone exposed on the foreshore at Lavernock, Glamorgan; see also Fig. 113.

(*Photo F.F.M.*)

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* Beyond saying that a colloid, or as it may be better expressed, a substance in a colloidal condition, is one that does not readily diffuse through membranes of a material like parchment, whereas a solution of the same substance in a crystalline condition passes readily through such a membrane, it is not possible to enlarge here upon the subject of the operation of concretionary forces. For a discussion of the principles involved, a recent work on physical chemistry should be consulted [12a, 12b].

being the clayey matrix. The deposition in any layer would begin at many points, and the knots of calcareous material would gradually increase in size until in many cases they met, forming the continuous but hummocky beds in which they frequently occur: in cases where they failed to meet, there would be bands of isolated nodules embedded in the shales.

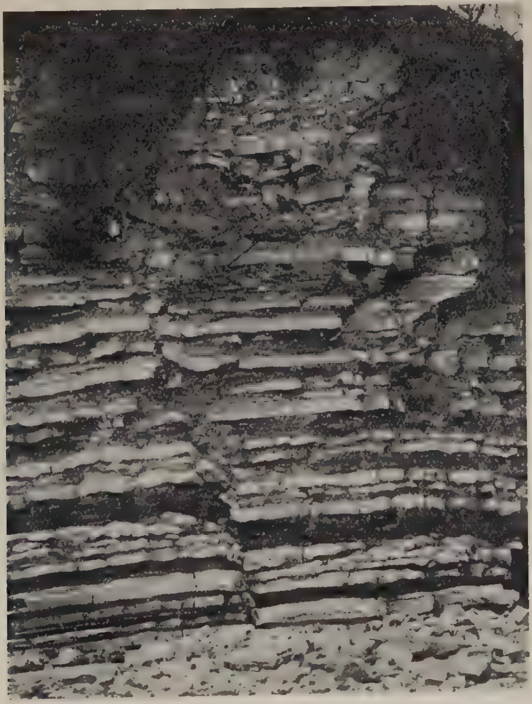

FIG. 113.—NODULAR LIMESTONES IN THE LIASSIC FORMATION.

Many of the beds of limestone in the Lower Lias have a nodular structure and probably result from the redistribution of calcareous matter in a deposit that was originally more or less homogeneous. (Barry Harbour, Glamorgan.) (*Photo F.F.M.*)

In the case of the Lower Lias of South Wales the original deposit must have been a calcareous mud derived from the denudation of a land area made up largely of Carboniferous Limestone, and it has been suggested [12] that the alternation of deposit was governed by slight changes in the salinity of the water: the matter is not, however, at present fully understood, and the explanation of the phenomenon will probably emerge as a result of experimental work. In some respects the problems resemble those connected with the formation of flint (see page 259) which is believed to have involved the redistribution and rhythmic deposition of silica that was once disseminated throughout the Chalk; see Additional Note, page 448.

Limestones in the Middle and Upper Liassic strata. — The Middle and Upper Liassic strata are similar in their distribution to those of Lower Liassic age, but they are, on the whole, sandy and argillaceous, and do not include extensive deposits of commercially important limestone.

On the Dorset coast between Charmouth and Bridport there are thick clays with limestone nodules and some calcareous flagstones in the Middle Lias, while the Upper Lias is for the most part sandy. At the top of the middle division there is a thin ferruginous limestone (the Marlstone) which becomes thicker when traced through Somerset into Gloucester, where it is often quarried, as for example at Dursley and Stinchcombe. The Marlstone also occurs and is quarried in Northamptonshire and Rutlandshire. It is usually bluish grey or greenish, except near the outcrop where weathering has produced a brown colour, and it is used locally for rough building work; the weathered stone is preferred for this purpose, not because it is of better quality, but because the fresh rock tends to discolour on exposure to the atmosphere.

The *Hornton Stone* of Edgehill, Warwickshire, is also of Middle Liassic age. It is a soft stone (of which there are both brown and green varieties), is easily sawn, and has been much used locally, especially in churches, and for steps, paving slabs, and tombstones.

A thin but interesting limestone, known as the "Junction Bed," occurs between the Middle Lias and the Upper Lias on the Dorset coast and has recently been described in detail [13, 14]. The total thickness is from 18 to 30 inches, and some of the rock is a very hard, platy limestone, with the texture of lithographic limestone.

Lithographic limestone, it may be mentioned in passing, is a fine-grained, compact, flaggy rock, used in the litho-printing process. Its value depends upon its capacity for absorbing grease and upon the fine polish that can be imparted to its surface. The design is drawn upon the stone with greasy ink, and when fixed in a suitable printing machine a water-charged roller is passed over the surface. The greasy ink of the design prevents water from settling upon those parts of the stone that had been covered, but where there is no design the surface of the stone is wetted. When the ink roller is passed over the stone, since the grease and water are mutually repellent, the printing ink only remains on those portions of the stone that had been prepared to receive it. Practically all the lithographic limestone of industrial use is a yellowish or bluish grey rock derived from the quarries of Solnhofen and Pappenheim in Bavaria.

There are no commercially important limestones in the Upper Lias.

When traced towards the north, the limestones in the Liassic formation tend to be replaced by ironstones. The change begins in the midlands, where the *Frodingham Ironstone* of Lincolnshire—which consists of thinly bedded oolitic and shelly ferruginous limestones alternating with limestones that are less ferruginous — occurs in the Lower Lias, and the *Banbury Ironstone* of Oxford replaces the Marlstone of the Middle Lias. The ironstones are, however, best developed in Yorkshire, where the important *Cleveland Ironstone* occurs in the Middle Lias; part, at least, of this ironstone is the equivalent of the Marlstone of the south.

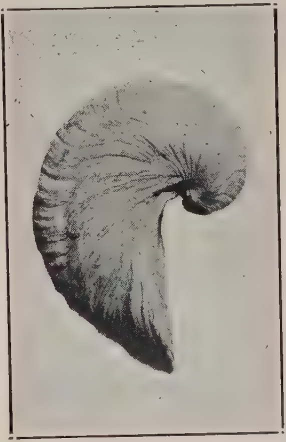

FIG. 114.—A CHARACTERISTIC LIASSIC FOSSIL.

Gryphæa arcuata (Lamarck) from the Lower Lias of Lavernock, Glamorgan; slightly reduced.

The ironstones appear to be altered limestones, the calcium carbonate of which has been largely replaced by ferrous carbonate, which in some cases has been oxidised and converted into ferric oxide, or hydrated ferric oxide (limonite). Owing to the ease with which they can be quarried, as compared with the hæmatite iron ores of Cumberland and Glamorgan, that have to be mined, the Jurassic ironstones are of great importance in spite of the fact that in many cases the iron content averages only 30 per cent., being rarely as high as 40 per cent., and often as low as 20 per cent. A detailed account of the ferruginous limestones of the Lias is outside the scope of the present work, but they have been fully described in a Memoir of the Geological Survey [15].

The fossils of the Liassic limestones do not call for special comment. They are very abundant in some beds, and in addition to the marine reptiles already mentioned, include ammonites, belemnites, and mollusca; among the latter, oysters (*Fig.* 18) and the allied bivalve, *Gryphæa,* are conspicuous. *Gryphæa* (*Fig.* 114) may be compared to an oyster in which one valve is convex and has an incurved beak, and Dr. A. E. Trueman has shown that as members of the genus are traced upwards through the deposits of the Lower Lias, the convexity and the curvature of the beak increases (*Fig.* 115), so that the fossils are of assistance in recognising the relative position in the geological sequence of the strata in which they occur, just as in the case of the Carboniferous Limestone the strata have been "zoned" by means of corals and brachiopods [16]. The evolution of the gastropods present in the Lias has also been studied by the same author with a view to determining their value for the purposes of correlation [17].

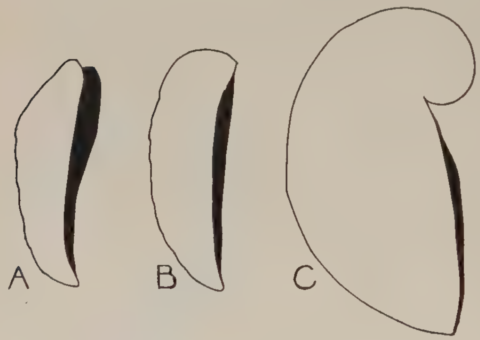

FIG. 115.—DIAGRAMS ILLUSTRATING THE EVOLUTION OF *Gryphæa,* in the Lower Lias (after A. E. Trueman). The shells are drawn as seen from the side. *A* is a species of *Ostrea,* and *B* and *C* two species of *Gryphæa,* from successively higher beds in the Lower Lias: the curvature and convexity of the left valve show a progressive increase from lower to higher beds; the right valves are represented by solid black.

Some early views concerning fossils. — The Liassic fossil, *Gryphæa,* provides interesting instances of the superstitions formerly associated with fossils, and of the uses to which they were put before William Smith showed how to use them in recognising and correlating the strata. Thomas Pennant in his "*Tour in Scotland, and voyage to the Hebrides*" (1772) tells us that in Scotland the shells were used as amulets, it being supposed that they had the power of curing pains in the joints, and in Gloucestershire, at Awre, the same fossil, powdered and mixed with whey, was used as a cattle medicine as late as the early part of last century [18]. In the same county, belemnites (*Fig.* 136) also have been credited with valuable medicinal properties: according to John Woodward, in the early part of the 18th century they were used by the farriers to cure watery affections of the eyes of horses: the fossils were ground and the powder blown into the animals' eyes. The same writer also records that the "common Pharmacologists recommend it inwardly" as a specific for kidney trouble! [19].

Some of these quaint beliefs are probably to be attributed to the mystery then attached to the origin of fossils. It is not possible to enter into a full account of this interesting subject which involves the early history of the whole science of geology [see, however, 20, 21, 22, 23], and it must suffice to say that during the seventeenth and eighteenth centuries the bodies we now call fossils gave rise to animated and often acrimonious controversies. The orthodox view was that they were relics of the Noachian Deluge, but other suggestions, hotly contended for, were, that they were simply the result of crystallising forces in the strata; that they were produced by a mysterious vital force which sometimes succeeded in making the shape of animals or plants but failed to endow the objects with life; that they were produced by the influence of the celestial bodies (this, no doubt, because of the star-like appearance of the stem-fragments of some sea-lilies or crinoids); that they were the remains of animals eaten by the earth's former inhabitants; that they were placed in the rocks by the Devil to assist him in subverting credulous man; and that they were placed there by the Creator for purposes best known to Himself.

Although a few writers, less romantically inclined, had pointed out objections to all these views, urging that fossils were merely the remains of animals and plants that had lived in past periods of the earth's history and had been entombed in the rocks as they formed, it was not until towards the end of the eighteenth century that this simple explanation—which became the foundation of geology—received serious consideration.

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CHAPTER X.

LIMESTONE IN THE JURASSIC SYSTEM: THE OOLITES.

> "To the laborious work of William Smith we are indebted for the first attempt to distinguish the various subdivisions of the Secondary rocks. . . . He did not cull euphonious terms from Greek or Latin lexicons, hence were introduced into geological literature such words as Purbeck Stone, Cornbrash, Clunch, Lias, and Forest Marble."
>
> Sir A. Geikie [33].

There must have been a rapid transition from the moderately deep water in which the Upper Lias clays accumulated, to the shallow water of Lower Oolite times, during which the deposits were mostly limestones and sandstones. Locally, there are gaps in the rock-sequence, indicating that some of the topmost beds of the Lias had been raised to, or above, sea level, and removed by denudation soon after their formation, with the result that the strata of the Inferior Oolite Series sometimes rest upon beds that do not represent the actual top of the Lias; this is more noticeable in the North (Yorkshire) and the Midlands, than in the south of England.

In the south-west, the strata are mainly shelly marine limestones with clays and sandstones, but as they are traced northwards the rocks become more sandy and ferruginous, and instead of typically marine fossils, they contain freshwater and estuarine shells such as *Unio*, the freshwater mussel, and *Modiola,* the horse-mussel, and they include thin beds of lignite and the remains of land plants. Rocks of this type make up much of the Lower Oolites of Northamptonshire, Rutland and Lincolnshire, and they indicate an approach to the shore of a land drained by a river, or rivers, flowing from the north. Yorkshire was still nearer to the land region, because there the deposits are mostly of a sandy character and they contain thin seams of lignite or of coal. In the north as well as in the south there was renewed subsidence towards the close of the Lower Oolitic period because the succeeding deposits were laid down under marine conditions.

The rocks of the Oolitic series are so variable and interesting that to describe adequately all the variations — horizontal and vertical—which the rocks display, would necessitate a stratigraphical discussion more detailed than the present occasion justifies, and all that can be done is to refer to the divisions in which limestones occur. For a similar reason the fossils must be dismissed with the bare statement that, on the whole, they resemble those of the Upper part of the Lias: ammonites (*Fig.* 116), and other molluscan groups are particularly well represented, while brachiopods, sea-urchins (*Fig.* 117), and corals are also abundant at some horizons. Fishes and reptiles occur, but of special interest is the occurrence in the *Stonesfield Slate* (thinly bedded calcareous rocks near the bottom of the Great Oolite Series) of some of the earliest known mammalian remains in this country; they comprise jaws belonging to very small insect-eating marsupials (animals pouched like kangaroos), and they

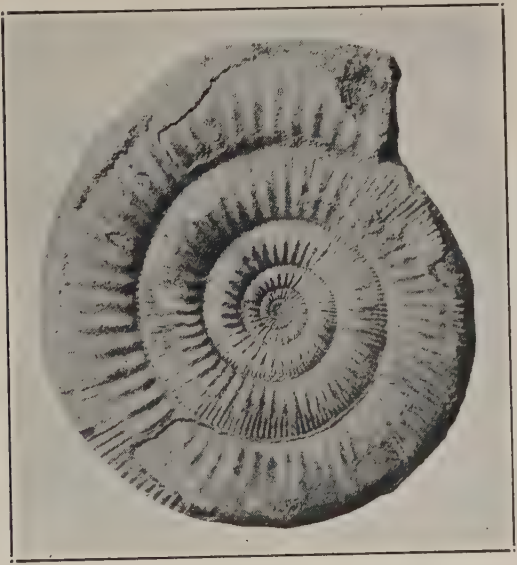

FIG. 116.—AN AMMONITE FROM THE OOLITES.

Ammonites humphriesianus (Sowerby) from the Inferior Oolite of Dundry; about one-third natural size.

gave rise to much discussion among palæontologists in the early part of last century.

Limestones in the Inferior Oolite Series.—The Inferior Oolite Series is over 250 feet near Cheltenham where it is best developed, (*Fig.* 118) and it includes oolitic limestones (freestones), ragstones and calcareous grits, but in Northamptonshire the strata are much thinner and constitute part of the sandy ironstone series known as the *Northampton Sand.* In Yorkshire the representatives of the Inferior Oolite are mostly of estuarine origin, and they include shales and sandstones with plant remains, calcareous and ferruginous grits, and a thick group of calcareous and siliceous beds with shaly partings, known as the *Scarborough,* or *Grey Limestone Series.*

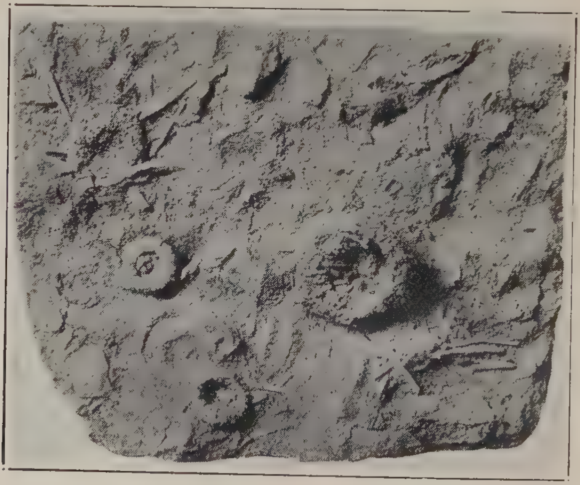

FIG. 117.—LIMESTONE WITH SEA-URCHINS OR ECHINOIDS.

From the Cornbrash of Chippenham, Wiltshire; two-thirds natural size.

The Inferior Oolite yields many important building stones especially in Gloucestershire and Somersetshire—the stone from the former district being generally lighter in colour and finer in grain than that from the latter.

In the Cotteswold country, where the Lower Oolite limestones are well developed, they give rise to prominent escarpments, and have influenced the earlier domestic architecture of the whole district; in the hilly regions the houses are built of limestone, while in the adjacent clay (Lias) vales they are constructed of bricks and timber. Many of the fine old stone houses that are so characteristic a feature of the Cotteswold country belong to the period (1580-1690) when the local wool-trade was in so prosperous a condition that much money was available for building houses and churches [2].

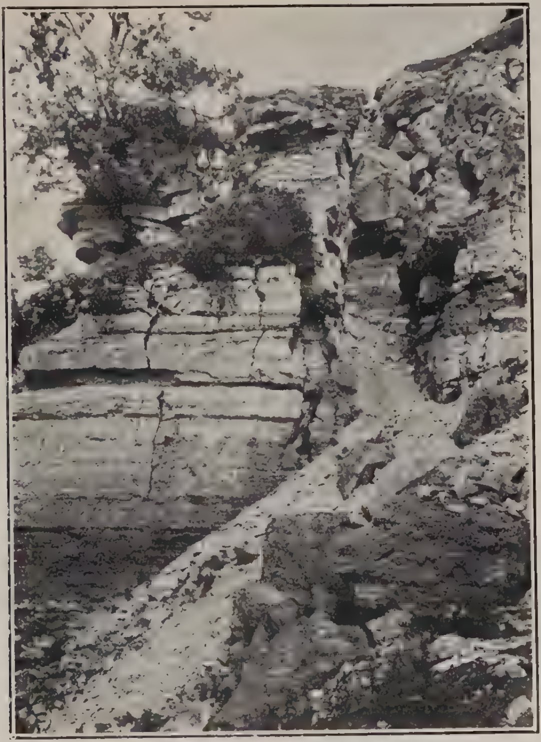

FIG. 118.—CRAGS OF OOLITIC LIMESTONE.
The Inferior Oolite at Cleve Hill, Cheltenham, showing bedding, and the effect of joints in facilitating denudation. (*Photo Frith and Co.*)

The following section of the strata at Leckhampton will serve to illustrate the general character of the limestone succession [1]:—

	Feet
"*Ragstone*"—a rough, shelly, oolitic limestone, not used for building	38
Upper Freestone—white or light yellow oolitic limestone, used for ordinary buildings	34
Oolite Marl—soft chalky limestone and marl	7
Lower Freestone—fine-grained, compact oolitic freestone, white or light yellow, used for building purposes ...	147
Pisolite, or Pea Grit—largely friable limestones, oolitic, shelly or coralline and unfit for building purposes ...	38

It should be noted that the term *Freestone* is applied to a stone (either sandstone or limestone) that can be cut easily in any direction, being comparatively free from obvious planes of lamination. Beds in which shells or large fragments of shells are abundant are *Ragstones,* and *Weatherstone* is a name applied to almost any parts of the limestone that are able to resist the decomposing action of the weather, and can, therefore, be used in exposed situations. Even in the case of Freestone, however, most forms possess lamination, and even although it may not be apparent in the fresh rock it usually reveals itself as the stone weathers; consequently in the case of monolithic columns such as play an important part in many architectural designs it is necessary that the blocks should be cut at right angles to the bedding, so that the planes of lamination pass horizontally across the columns. Sometimes in order to secure longer shafts an apparent freestone is cut so that the bedding planes run vertically through it, but weathering may emphasise lamination and the stone may flake, thus spoiling the appearance of the column, as proved to be the case with some of those in the London Law Courts [3].

Among the building stones of Inferior Oolite Age are the following: *Ham Hill Stone* (named from a locality near Norton-sub-Hamdon in Somerset), which is a brownish limestone consisting mainly of broken shells cemented by ferruginous matter. The rock is obtained in large blocks, and weathers well in the local country air. It has been worked for many centuries and Roman coffins made of it have been found [4].

The Ham Hill Stone occurs in the lower part of the Inferior Oolite Series, and is really a local calcareous development of the sandy beds known as the Midford Sands; similar stone occurs near Yeovil.

At Doulting, near Shepton Mallet, oolitic rocks occur near the top of the Inferior Oolite. Some of the beds yield freestone, and others are limestones with crinoidal fragments; this suggests that the rocks were derived from the waste of Carboniferous Limestone, upon which rock the Inferior Oolite rests in the eastern Mendip region.

The *Doulting Stone* is usually uniformly light brown or buff in colour, and of even grain. When first quarried it is soft and earthy looking, but it hardens on exposure, and weathers well. It has been extensively used, as for example in the earlier parts of Wells Cathedral, and in Glastonbury Abbey. It has also been used more recently in restoration work in many cathedrals and churches, including those at Bristol, Exeter, Llandaff, and Winchester, and in churches, hotels, and other buildings in London.

Dundry Stone, obtained from mines and quarries at Dundry Hill near Bristol, is a cream coloured shelly limestone, less uniformly oolitic than many other limestones of the same age. The bed worked for building purposes is only about six feet thick, and examples are to be seen in Bristol (St. Mary Redcliffe Church), Cardiff (St. John's Church), and in the restoration work in Bristol Cathedral and Llandaff Cathedral.

Painswick Stone, from Painswick Hill near Stroud, is a cream coloured soft oolitic rock, on the whole of paler tint and finer grain than those found farther south. It strongly resembles the Caen Stone of Normandy, and has been extensively used for fireplaces, mouldings and interior work generally, but does not withstand exposure in damp situations. It was used in restoring Gloucester Cathedral and the interior of the War Office building in London.

Nailsworth Stone is an oolite of uniform grain obtained from underground workings (*Fig.* 219) near Nailsworth, and used for interior work, while *Ball's Green Stone* from the same neighbourhood is a light coloured rock resembling that of Painswick.

Other Inferior Oolite limestones are worked at Bourton-on-the-Hill, Birdlip, Stroud, and Chipping Campden, near Evesham.

Most of the foregoing building stones are derived from the middle part (the Freestone division) of the Inferior Oolite. Below that division there are beds of "pea-stone" or pisolite (a rock which resembles an oolite with very large and somewhat irregular grains (*Fig.* 119), and above it are ferruginous and oolitic shelly limestones (ragstone), which do not as a rule yield good building stones.

In Oxfordshire, the most important calcareous division of the Inferior Oolite is the *Chipping Norton Limestone,* which occurs near the top of the Series, and consists of oolitic and sandy limestones, of little economic value except for rough building.

In the midland counties the upper part of the Inferior Oolite is represented by the *Lincolnshire Limestone* and the *Collyweston Slate.* The Lincolnshire Limestone series comprises variable marine limestones, sometimes shelly, sometimes coralliferous, and occasionally oolitic. One of the most interesting varieties is the *Barnack Stone* of Northamptonshire which, although not now obtainable, was worked for many centuries, and is mentioned in documents (dated A.D. 664) relating to the building of Peterborough Cathedral. There is a record that eight pairs of oxen were required to move one block of stone from Barnack. In the 11th and 12th centuries the stone was extensively used in the cathedrals and abbeys of East Anglia, but the supply seems to have been exhausted by the 15th century.

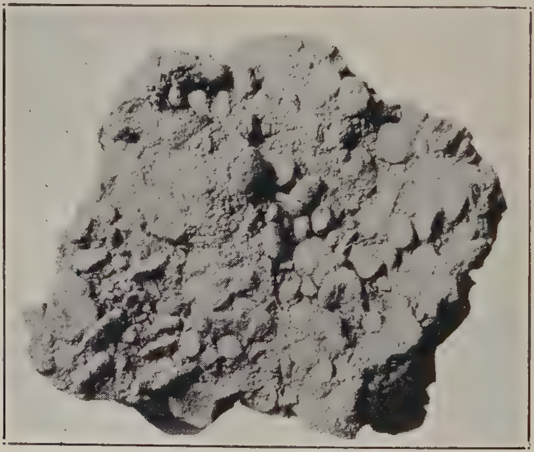

FIG. 119.—PISOLITE OR PEA-GRIT.
Inferior Oolite, Leckhampton Hill, Gloucestershire; about two-thirds natural size.

The *Weldon Stone* of Great Weldon, Northamptonshire, also belongs to the Lincolnshire Limestone group. There are several varieties which are, on the whole, more shelly than many of the limestones in the Oolitic Series, and, owing to their open texture they are better able than many rocks to resist the disintegrating action of frost. Some varieties are cream coloured, and others have a pinkish tinge. It is said that Weldon Stone was used in Old St. Paul's (destroyed in the Great Fire of 1666) and there are numerous examples of its use in Cambridge; there is a record that Henry VII. presented a quarry yielding Weldon Stone to King's College, the chapel of which is partly built of it.

The name *Ketton Stone* is applied to certain limestones quarried in the county of Rutland; the original Ketton Stone which has been for long unobtainable, was a fine, even grained oolite, pinkish cream in colour, and generally similar to the stone now marketed as Ketton Stone which is a strong, durable rock, porous, and although easy to work, hardens on exposure; it is one of the stones selected for use in the repairs to the Houses of Parliament. Like most of the other Inferior Oolite Limestones, Ketton Stone has been used in ecclesiastical and other buildings, as for example, St. Dunstan's Church, London, the Cathedrals at Peterborough and Ely, the dressings of St. Pancras Railway Station, and in some of the Cambridge colleges. *Casterton Stone* is a similar rock from a quarry east of the original Ketton Quarry.

In the Ketton Quarries there is also a dense oolitic rock in which the spaces between the oolites have been completely filled with crystalline calcite. The bed is about three feet thick, and the rock, known as *Ketton Rag,* was used in York Minster and in the Tower of London. Recent developments in connection with the manufacture of Portland Cement and rapid-hardening cement, in which the limestone and clays of Ketton are being used, will, it is anticipated, result in the re-exposure of the original Ketton Stone.

Ancaster Stone, from a place of that name near Sleaford, Lincolnshire, is a cream or buff tinted oolite; it is usually of fine grain, although some beds contain broken shells and are coarser in texture. The rock is a freestone, easily worked, obtainable in large blocks, and hardens on exposure. A coarse shelly variety with much crystalline calcite is known as *Ancaster Rag.* The limestones of Ancaster are suitable for most building purposes, and were used, among other places, in Lincoln Cathedral. The Rag or "Weather Bed" is harder than the ordinary Ancaster Stone, and is suitable for use in situations where it is likely to suffer abrasion due to traffic. This is, for example, the case in the south wall of the New Medical Schools, Cambridge, where the lower courses are of the mottled Ancaster Rag Bed, and the upper ones of the uniformly tinted brownish Ancaster Stone.

Other members of the Lincolnshire Limestone Series that are of commercial use include the *Haydor Stone,* from Haydor, near Grantham (which in appearance and properties resembles the Ancaster Stone), the *Glendon Stone* (a fine-grained brownish sandy limestone much used near Kettering) and *Clipsham Stone* (a fine grained limestone with occasional shells, used in and around Cambridge, and in the restoration of the cathedrals at Ely, Peterborough, and Norwich). The *King's Cliffe Stone,* a light yellow shelly limestone from a locality west of Peterborough, was also used in some of the early Cambridge buildings, but the quarry has long since ceased to exist.

Almost the only limestone of this series in Yorkshire that has been used for building is that near Aislaby, south-west of Whitby. It is a sandy limestone from the Lower Estuarine Series, and has been used for building in Eskdale; it is to be seen in the 13th century abbey at Whitby.

The foregoing examples, which are by no means exhaustive, are sufficient to indicate the extensive range of variety and use, and the wide distribution of limestones in the Inferior Oolite Series.

Limestone in the Great Oolite Series. — From the table of strata, *Fig.* 97, it will be seen that the Great Oolite Series includes important clay deposits as well as limestones.

The *Fuller's Earth* is a marly clay, blue or grey in colour; some parts of the deposit yield the Fuller's Earth of commerce (the value of which lies in its affinity for grease), and it includes also an earthy limestone—the Fuller's Earth Rock—which is of no economic use. The Fuller's Earth is best developed in Dorsetshire, but north-east of Bath it diminishes in thickness and loses its identity.

The Great Oolite, proper, is a limestone formation occurring above the Fuller's Earth (where that deposit is present); it is thickest in Gloucestershire, where it yields the famous "Bath" stone, and it includes shelly limestones and fine grained oolitic freestones. The lower part of the Great Oolite is often sandy and flaggy, and where the flaggy character is best developed the rock has been used for tilestones. This is the case, for example, near Woodstock, Oxfordshire, where the *Stonesfield Slate* has been quarried for a long period (see page 214).

The *Forest Marble* is a group of shelly limestones, sometimes oolitic and sometimes flaggy, associated with clays and sand; it is very variable, and of it, the *Bradford Clay* (a fossiliferous clay occurring near its base at Bradford-on-Avon), is really only a local development. The Forest Marble is not generally as useful as the other limestones of the Lower Oolites, but some varieties are suitable for building, and are quarried in many localities, *e.g.*, Long Burton, North Cheriton, Frome (*Frome Stone*) and Cirencester. It received its name on account of its occurrence in Wychwood Forest, Oxfordshire, and because some of its shelly oolitic beds were found suitable, when polished, for use as "marble" in constructing mantelpieces.

One of the features of the work of William Smith was that he drew attention not only to the fossils of the successive strata that enter into the make-up of our country, but also to the possibility of recognising the outcrops of particular rocks by noticing peculiarities in the vegetation they support or in the surface features to which they give rise. Speaking of the Forest Marble he wrote, in 1815:—

> "The locality of the forest marble may be known in many parts of the narrow district which it occupies, by the common use, in the villages, of the coarse large flat-stones and rough slate which it produces. The cottage gardens are fenced with these flags, set on edge, in many of the villages near the quarries" [31].

As is the case with the Inferior Oolite Series, the Great Oolite Series also changes in character towards the north. In the south, the strata are all marine deposits that accumulated in shallow water, but when traced through the midlands into Yorkshire, estuarine beds become increasingly important. The exception to this general rule is the topmost division of the series (the Cornbrash), which although thin—only from 10 to 20 feet in thickness—retains its character as a marine deposit almost unchanged throughout its entire outcrop. It is one of the most persistent beds in the whole of the Jurassic System, and as such is of great value in the correlation of the strata. Recent work upon its fossils suggests, however, that the Cornbrash is not constant in its geological horizon, being somewhat younger in the north than in the south, evidently because the conditions under which it was formed commenced earlier in the south and moved progressively northwards [6].

The Cornbrash includes rubbly, somewhat ferruginous, limestones, that are rarely suitable for use as building stones, although it has been quarried for that purpose at Upton Noble in Somerset. Its chief interest, apart from its geological significance, to which reference has just been made, is the character of the soil derived from it. The rock breaks up readily and gives rise to a "brashy" soil—that is a fairly light loam, well adapted for corn-growing—hence the name Cornbrash, which is an old agricultural name that was adopted by William Smith, when, towards the end of the 18th century, he first began to describe and classify the rocks of this country in connection with the preparation of his geological map [7]. The Cornbrash soils are more fertile in the south than in the north, where the rock is somewhat ferruginous and oolitic. The Cornbrash, as we have already seen, marks a period when, after local earth-movements had given rise to estuarine and shore conditions over the midlands and the north of England, marine but shallow water conditions once more prevailed over the whole country for a brief period.

Having considered the Great Oolite Series as a whole, it now remains to refer to the important building stones derived from the "Great Oolite" proper. From their development in the neighbourhood of Bath, especially in the hilly region east of the city, the beds are also known as the *Bath Oolite* and the numerous varieties of the rock as *Bath Stone*.

In general the Great Oolite comprises oolites and shelly limestones at the top, oolitic freestones in the middle, and shelly and marly limestones below; the freestone division, which is from 8 to 30 feet in thickness, is the most important, but the sequence of beds varies enormously from place to place. As a rule the Bath Stone is a light coloured oolite; some varieties are of finer grain than others, but all are comparatively soft and easily worked when fresh, tending to bleach and harden on exposure, as is the case with most of the Jurassic limestones; freshly mined blocks are stored in order to allow the stone to become "seasoned"; see also page 381.

The rock has been worked at least since the Romans occupied Bath, for the stone was used in the buildings they erected around the local hot springs, and it has been employed in ecclesiastical and domestic architecture throughout the subsequent centuries. At the present time the stone is obtained from underground mines reached either by levels driven into the hillside, or by shafts sunk to meet the desired bed.

Among the varieties of Bath Stone are the following:—

Box Ground, long quarried near Box Hill, and also called *St. Aldhelm Stone*, on account of a legend that it was discovered by St. Aldhelm, a seventh century Bishop of Sherborne. The rock is finer in grain than most of the Great Oolite limestones, and is one of the best varieties for use in exposed situations. It has been extensively used in London as well as locally.

Corsham Down Stone is an oolite of fine and even grain, which can be obtained in large blocks. The stone is suitable for inside work and is an excellent freestone; *Monks' Park Stone* is similar.

Farleigh Down Stone (Monkton Farleigh) is perhaps the least expensive of the Bath Stones, and is best suited for inside work. It is fine grained, even in texture, and has a warm creamish colour.

Coombe Down Stone, obtained from a locality south of Bath, is darker in colour (pale brown) than some of the other varieties, and although it often contains veins of calcite, has good weathering properties; it was used, among other places, at Buckingham Palace.

Other varieties are *Bradford Stone* (Bradford-on-Avon), *Stoke Ground Stone* (Limpley Stoke), *Winsley Ground,* and *Westwood Ground, Hampton Stone* (from Bathampton Down). *Windrush Stone,* and *Taynton Stone,* although formerly worked, are not now of importance; a variety of Taynton Stone (from near Wychwood, Oxfordshire) was used in many of the early Oxford colleges. The *Guiting Stone* of Gloucestershire is coarser in grain than many of the oolitic stones previously described and has a brownish orange tint; it was used in some of the Oxford colleges (St. John's, Christ Church); see Additional Note, p. 448.

Caen Stone.—Although the domestic supply has always been sufficient to supply the country's needs, certain foreign limestones have from time to time found a place in British architecture, and although this work is concerned primarily with the limestones of our own country, at least one stone of foreign origin is of sufficient interest to be mentioned: it is the Caen Stone from Calvados, Normandy. This is a fine grained comparatively soft oolite, not unlike the Bath Stone, near to the geological horizon of which it occurs. Its introduction to England began soon after the Norman Conquest, and it was used in several important buildings.

The stone is capable of being finely carved, and although suitable for interior work (for example, the columns in the Museum of Practical Geology, Jermyn Street), it does not withstand the destructive effects of town air, as proved to be the case with the Carlton Club in Pall Mall, and St. George's (Roman Catholic) Cathedral in Westminster Bridge Road. Its unsuitability for exterior use in London was recognised by Christopher Wren who, referring to Henry's VII.'s Chapel, Westminster, wrote:—" A nice embroidered work, performed with tender Caen Stone, and though lately built in comparison, it's so eaten up by our weather that it begs for compassion."

Stone-tiles or "Slates" in the Oolitic Series.—These occur at several horizons and are for the most part calcareous sandstones or sandy limestones, with more or less mica; the limestones are generally oolitic. Unlike true slates, which can be split in the direction of cleavage into layers of almost any desired thickness, the English Jurassic "slates" split only along planes of deposition, the distance between which determines the thickness of the slab.*

The Jurassic stone-tiles have been known since the time of the Romans, but they are used much less now than in the past, and in many districts the industry has long since died out [9, 10],

The slates are derived from three principal horizons:—

Inferior Oolite (*Collyweston Slate*).
Great Oolite (*Stonesfield Slate*).
Forest Marble.

Collyweston Slate has been worked for centuries near Collyweston in Northamptonshire, and mediæval records contain many allusions to it. In the fourteenth century, the slates were worth from 6s. to 8s. per thousand [11]. The "slate" bed is quite thin, varying from six inches to eighteen inches, and it is worked partly in open quarries and partly underground. The material is removed by means of wedges, because it is injured by blasting, and it is usually dug only for a few weeks before and after Christmas. The blocks are laid on the ground and kept moist until frost sets in, for until "frosted" the rock cannot be satisfactorily split; if the block dries before it is frozen the stone becomes useless except as road metal. If exposure to frost is not sufficient to lead to the splitting of the stone, it becomes impervious to frost action afterwards, and in winters when little frost has occurred vast quantities of stone that has been raised have been spoilt and the supply temporarily stopped.

In their reaction to moisture and frost the Collyweston slates differ from true slates, in which the natural moisture in freshly quarried material adds to its flexibility and the ease with which it may be split. If allowed to become dry or exposed to the frost the tendency of true slate to cleave is impaired, and instead of being exposed before splitting, the blocks are carefully protected, especially in the case of those obtained from underground workings. Collyweston slate is bluish in colour, weathering buff, so that roof-tiles made from it may be either blue, buff, or mottled.

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* Cleavage is a property possessed by slate and other rocks that have been subjected to intense pressure during periods of earth-movement. The result of the pressure and the heat by which it was accompanied is that the particles of the original sediment (in the case of slate it was usually clay) have been re-arranged until they all lie more or less in the same direction—that is, transversely to the direction of pressure, while flaky crystals of new minerals such as mica have been developed between them. Such altered rocks no longer break up into sheets corresponding to the layers or beds in which they were deposited, but can be split (cleaved) into thin sheets of almost any desired thickness, in a definite direction that is related to the structures induced by the earth-pressure to which the change was due [8].

Other beds in the Inferior Oolite have been worked for tile-stones, as for example the *Duston Slate Bed* of Northamptonshire, while near Bradford Abbas the Inferior Oolite has yielded paving slabs.

The *Stonesfield Slate* occurs at the base of the Great Oolite, and is mostly quarried near Woodstock in Oxfordshire, although similar rock occurs in many other places at the same horizon. The slates are derived from thinly bedded sandy oolitic limestones, from thirty inches to thirty-six inches thick, and the workings are mines reached by shafts. As in the case of Collyweston Slate the blocks have to be exposed to the action of frost before they can be split, and a mild winter is, therefore, often disastrous to the slate workers; see Additional Note, page 449.

The Stonesfield Slates vary in colour from brown to blue, and while some beds are calcareous sandstones, others are limestones more or less oolitic. Their early use is thus recorded by Dr. Robert Plot, Keeper of the Ashmolean Museum, in his "*Natural History of Oxfordshire,*" 1677:—

> "But before we take leave of materials for Building, we must not forget that the Houses are covered, for the most part in *Oxfordshire* (not with tiles) but *flat-stone*, whereof the lightest, and that which imbibes the water least, is accounted the best. And such is that which they have at *Stunsfield*, where it is dug first in thick cakes, about Michaelmass time, or before, to lye all the *winter* and receive the frosts, which make it cleave in the *spring* following into thinner *plates*, which otherwise it would not do so kindly" [12].

The Forest Marble yields tile-stones in Wiltshire, Gloucestershire and Oxfordshire, and at Poulton near Cirencester they were known as *Poulton Slates*. They occur as thin layers of limestone, often arranged obliquely and separated by horizontal layers of shale, that is to say, they represent a kind of false-bedding or current-bedding* (*Fig.* 120), and they do not require to be frosted in order to be split. They are heavier and coarser than the Stonesfield slates, but are said to be more durable [27].

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* False bedding or current bedding is due to the sorting action of the gentle currents while a deposit is accumulating; the smaller lines of stratification, instead of being more or less horizontal and parallel, as in a shale, are arranged diagonally and are inclined first in one direction and then in another.

The *Slatt Beds* and other fissile limestones in the Purbeck Beds of Portland have also been worked for roofing tiles and used locally, as for example at Weymouth; they are less durable than the Collyweston and Stonesfield slates, which they resemble in appearance, while similar stones from other localities have been used in Swanage, Corfe, and Devizes.

Of somewhat similar character is the *Horsham Stone* (from Horsham in Sussex) which, although it occurs in the Weald Clay and is of Cretaceous age, is conveniently included for reference here. It is a calcareous sandy rock readily splitting into slabs suitable for paving and roofing [26]. As a roofing medium the stone has been nearly if not completely replaced by the lighter slates and tiles, but as early as 1425 there is a reference to one, William Brooker, the *sclatter* of Horsham, who was employed in roofing the hall of the Draper's Guild [32]. The Horsham slates were locally known as " healing stones " from the Saxon *haelan*, to heal, or to cover, as with bedclothes.

FIG. 120.—FALSE BEDDING OR CURRENT BEDDING, in Carboniferous sandstone near Llangollen, North Wales. (*Photo F.F.M.*)

The origin of oolitic structure.—Oolitic structure is so characteristic of the Jurassic limestones, although it is by no means confined to them, that the present is a convenient occasion on which to refer to its origin. The essential feature of an oolitic limestone is that the rock consists largely or wholly of rounded calcareous grains more or less thoroughly cemented together. The grains may vary in size from smaller than a pin's head to as large as peas, but when they are large the rock is called "pisolite" or pea-stone (see *Fig.* 121). The individual grains, which are usually round but are sometimes ovate, are composed of calcium carbonate, and in thin sections they often exhibit a concentric structure, indicating that they were built up, layer by layer, by the deposition or accretion of material about a central nucleus such as a fragment of a fossil, a particle of sand, or a rolled fragment of calcareous mud; there is often also a distinct radial arrangement of the calcium carbonate, due to crystallisation.

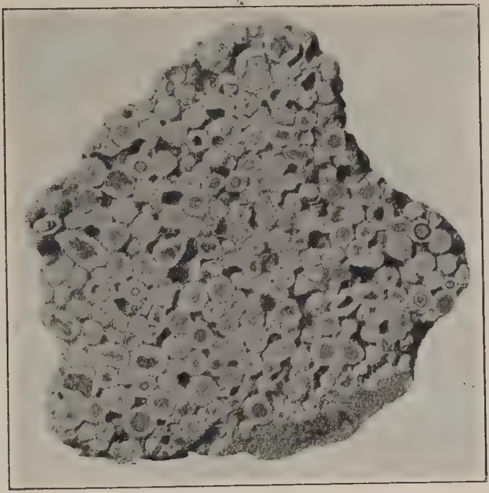

FIG. 121.—PISOLITE.

A pisolitic rock of recent formation: the Sprudelstein of Karlsbad, Bohemia; natural size.

Various conditions have led to the development of oolitic structures. In some cases the grains resulted from the deposition of layers of calcium carbonate around the nucleus, in shallow water highly charged with calcium carbonate, where the particles were continually disturbed by currents; in such cases the concentric structure is well displayed, and many oolitic rocks represent accumulations of grains formed in this way, and subsequently cemented together by the deposition of calcium carbonate in the spaces between them. In other cases, minute organisms, such as certain algæ that are capable of extracting calcium carbonate from the sea water, appear to have been responsible for the formation of oolite.

Many years ago, H. C. Sorby showed that the growth of the oolite grain was often a combination of chemical and mechanical processes, and that in addition to the deposition of calcium carbonate by crystallisation, there was a picking up of foreign matter as the grains rolled about [13].

At the present time, oolitic grains are forming locally on the shores of the Great Salt Lake of Utah. The water is highly charged with calcium carbonate, and where there is much surf the carbon dioxide, by reason of which it is held in solution (see page 297), is readily given off, and the calcareous material is deposited around minute nuclei; the rounded form of the grains is due to the fact that they are continually on the move [14, 15]. The material tends to drift shoreward in dunes, and to be consolidated by the action of percolating water.

As far back as 1853, de la Beche pointed out in his "*Geological Observer*" that oolitic grains are forming in the neighbourhood of the West Indian coral reefs; here the nuclei are fragments of shells, corals, or foraminifera, and the grains at first have the shape of the nucleus, but as layer upon layer of calcium carbonate is deposited they gradually become more and more nearly spherical; see also Additional Note, page 447.

Light is also thrown upon the conditions under which oolite grains accumulated by some of the beach deposits connected with the Great Barrier Reef of Australia. In his account of the voyage of H.M.S. Fly,* J. B. Jukes refers to a rock made up of small round grains, in texture not unlike some oolites. Near the surface it was hard enough to be used for building stone, but it passed downwards into a coarse and friable coral sand. Fossil turtle eggs were found in the compact part of the stone and it was evident that the consolidation of the stone had taken place after the material had been raised above sea level. He added, "It was due probably to the infiltration of rain water percolating through the calcareous sand that had been gradually piled above high water mark by the combined action of the winds and waves" [16].

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* Joseph Beete Jukes, who was one of Sedgwick's favourite pupils, served as naturalist on the expedition which in 1842 went on H.M.S. Fly to survey Torres Strait and the Great Barrier Reef of Australia; in this country he is, perhaps, better known for his work on the Geological Survey, especially in North Wales, and in Ireland.

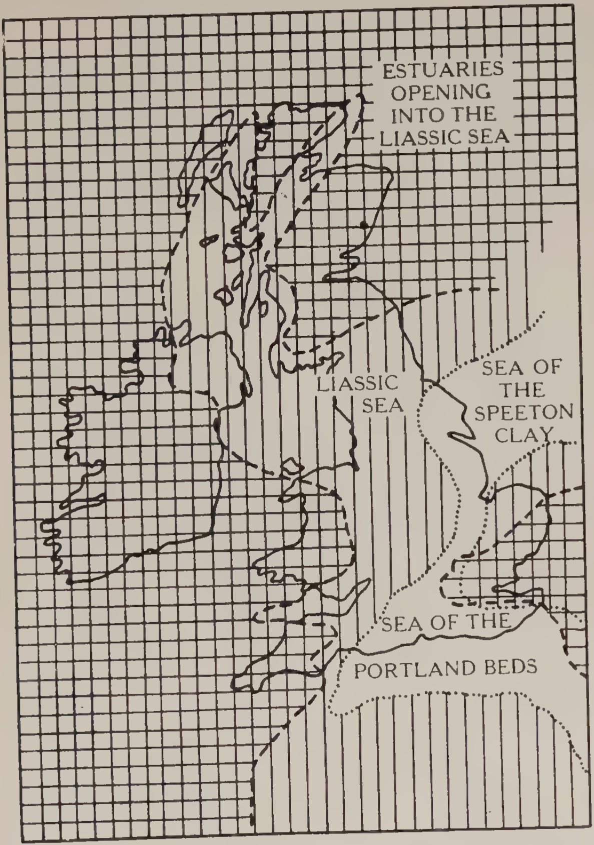

FIG. 122.—GEOGRAPHICAL CONDITIONS DURING THE JURASSIC PERIOD.

The sea of later Jurassic times was much smaller than during the Liassic epoch.

In this connection it is interesting to note that fossil reptile eggs have also been found in the Great Oolite of this country; see also page 222.

Grains large enough to be called "pisolitic" build up the *Sprudelstein* of Karlsbad in Bohemia, where the water from certain hot springs is charged with calcium carbonate, which is deposited as the water cools and is relieved from the pressure to which it is subjected when deep beneath the surface. Here, sand grains or minute fragments of granite act as the nuclei about which the pea-like bodies are built up as the calcium carbonate encrusts them. Algæ are believed to play an important part in the deposition of the Sprudelstein (*Fig.* 121).

In the layers of some oolitic and pisolitic grains there is a microscopic tubular structure, believed to be the product of a problematical organism—possibly a simple kind of alga, to which the name *Girvanella* was given when it was first detected in the Ordovician rocks of Girvan, Ayrshire [17].

The geographical conditions of oolitic times.—It will assist in understanding the distribution and variations of the Jurassic rocks if we again refer to a map incorporating what we know of the geography of the time (*Fig.* 122). There was a warm shallow sea, more or less enclosed like the Mediterranean of to-day, with numerous wide gulfs and bays. Rivers from the neighbouring land brought down mud and sand which gave rise to the argillaceous and sandy deposits, while corals flourished in the clearer parts of the sea, and many kinds of invertebrate animals were busily engaged in extracting calcareous matter from the water, incorporating it into their skeletons and making accumulations of material that were later to become limestones. At times, the shallow water, kept in motion by gentle currents, was heavily charged with calcium carbonate, the deposition of which, as a result of evaporation or of the work of minute organisms, gave rise to an abundance of oolitic grains.

Corals (*Fig.* 123) probably played a greater part in the formation of the Jurassic limestones than their occurrence as fossils indicates, because many of the reefs must have been destroyed during the periods of slight uplift and local denudation that were so important a feature of Oolitic times, and their disintegrated remains no doubt provided a good deal of the calcareous material of the oolites.

Owing to the frequency with which local uplift caused newly formed deposits to be removed and re-distributed on the floor of the adjacent shallow sea, the thickness of the Jurassic rocks is, as we have seen, no indication of the length of Jurassic times. On the whole, the crustal movement from Liassic times onwards was one of subsidence, which, however, was neither uniform nor continuous. The marked lateral and vertical changes in the strata indicate that the conditions were such that a very slight movement would affect the nature of the deposit accumulating over a wide area. When the sea occupied the gulfs (as it would during periods of depression) the river mud would be deposited at the head of each estuary and the water of the main part of the sea would be clear and favourable to limestone formation, but as the land-derived sediment built up deltas and filled the gulfs, the muddy material would be carried farther and farther from the land until it eventually came to be deposited as clay or sand on the floor of what had previously been the open sea. Slight warpings of the floor would cause the temporary isolation of small or large basins, in which deposits of one kind would accumulate contemporaneously with deposits of another kind elsewhere. Further reference to these local variations will be made in connection with the rocks to which they gave rise.

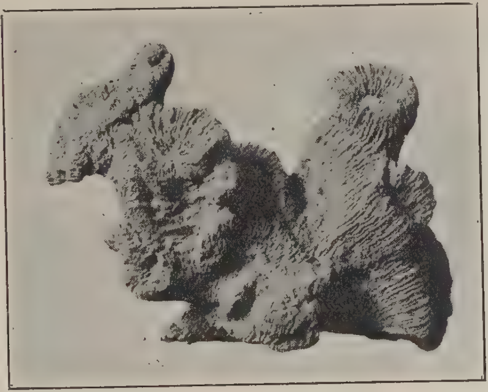

FIG. 123.—A FOSSIL CORAL.

Thecosmilia annularis (Fleming) from the Corallian Beds of Calne, Wiltshire; nearly natural size.

We have already had occasion to refer to the possibility of the occurrence of limestones that accumulated as a result of wind action, and interesting evidence bearing upon the matter is afforded by the Great Oolite. Many years ago, James Buckman recorded the discovery, in beds near the top of that series exposed in a quarry near Cirencester, of a group of fossil eggs, which, from their shape, were evidently those of some unknown kind of reptile. Buckman considered that the rock accumulated on a wide shelving beach adjacent to a shallow sea, for since a reptile breathes air throughout the whole of its life it is not likely that the eggs would have been laid where they were liable to be covered by the sea. Some years later, similar eggs, discovered in the Stonesfield slate [45], were found to correspond in shape and surface markings with those of turtles, and modern turtles are known to bury their eggs in holes scooped out of the sand, well above the reach of high water.

In the case of the Cirencester occurrence, the strata resting on those in which the eggs occurred were false-bedded oolites, the grains of which were such as could have been carried by the wind, as were also all the fossil fragments in the rock; and everything points to the conclusion that the material accumulated as a result of wind action, as is the case with some of the oolitic deposits now in process of formation. The general dip of the false-bedding is to the north-east, indicating that the prevailing wind came, as it does now, from the south-west, and the whole circumstance affords an interesting example of the nature and interpretation of the evidence for restoring the geographical and physical conditions of past periods. The false-bedded oolites are not confined to one stratum and they are separated by others that are normally stratified, so that it would appear that part, at least, of the Great Oolite Series consists of an alternation of deposits formed in shallow water, with others that accumulated on the shore as wind-blown material; see Additional Note, page 449.

The Middle and Upper Oolites. — These divisions of the Jurassic Systems are, on the whole, more argillaceous than the Lower Oolites. The Oxford Clay and the Kimmeridge Clay are thick and widespread, but there are limestones in the Corallian division between them, and the Portland Beds, although of local development only, are of importance as the source of Portland Stone; the Purbeck division also, is, in part, calcareous.

We have seen that the Cornbrash represents a time when marine conditions prevailed over the whole of the area where the English Jurassic rocks occur, and in the early part of the succeeding period (during the formation of the calcareous sandy beds constituting the Kellaways Rock, which occurs at the base of the Oxford clay) the conditions were even more favourable to marine life, and the fossils indicate that ammonites and other molluscs were particularly abundant. A fairly sudden change allowed mud-laden water to spread over practically the whole country—a condition that was maintained sufficiently long to permit the accumulation of many hundreds of feet of clay with marine fossils: These deposits constitute the Oxford Clay and the Kimmeridge Clay. In the south and in the north the accumulation of clay was interrupted by a temporary return to limestone-forming conditions, because the Corallian Rocks, with their corals and other fossils, indicate clear and shallow water.

The Oxford Clay is a particularly stiff bluish clay about 600 feet thick; it occupies a low-lying district extending from Dorsetshire by way of Oxfordshire to Lincolnshire, and is well displayed around Oxford, on which account it was so-named by Conybeare (*Fig.* 124), a former Dean of Llandaff, and joint author of one of the earliest books on English geology [18]. It is mostly given over to pasture lands.

The Kimmeridge Clay (named from the village of Kimmeridge on the Dorset coast) is about as thick as the Oxford Clay, but rather more shaly and marly. Near Kimmeridge itself the black shales are so heavily charged with bituminous matter that some beds have been locally used as fuel, and attempts have been made to use the rock for the purposes of oil shale. Where they are present the Corallian Beds form an elevated tract between the "vales" occupied by the Kimmeridge and Oxford Clays.

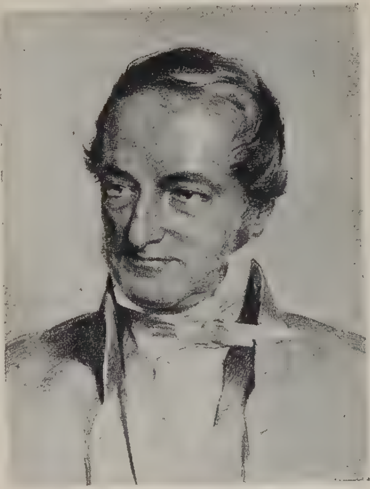

FIG. 124.—REV. W. D. CONYBEARE (1787-1857).

Rector of Sully, Dean of Llandaff, and a pioneer in the study of the rocks, especially the Jurassic rocks, of this country. (Reproduced by permission of the Council of the Geological Society.)

We have already seen from the earlier phases of the earth's history, that a period during which the movements are predominantly downwards, and during which marine conditions prevail, is always followed by earth movements leading to upheaval and the development of continental (land) conditions. This was, for example, the case at the end of the Silurian Period, as well as at the end of the Carboniferous Period; and as the Jurassic deposits are traced upwards we see that a similar set of changes was impending. After the accumulation of the Kimmeridge Clay, there were two separate areas of deposition, one in the north and another in the south. This was the result of an uplift in the south midland region, which, as *Fig.* 122 indicates, was already foreshadowed in earlier Jurassic times. In the south, the water again became clear and the marine Portland Beds—sands and limestones—were laid down, while in the north, if any beds were deposited at the time they were very soon eroded away, for none occur beneath the rocks of the next geological period, the Cretaceous.

The latest formed Jurassic deposits are quite different in the two areas; in the south, the sea of Portland times gave place to land, and the Purbeck Beds are for the most part of estuarine and freshwater origin; they include also certain layers ("dirt beds") which represent ancient soils formed on dry land. In the north, on the other hand, although there are no representatives of the Portland Beds, a marine clay—the *Speeton Clay*—was laid down while the Purbeck Beds of the south were accumulating. Thus, like some of the earlier geological periods, the Jurassic closed with the introduction of continental conditions, but unlike the arid deserts that replaced the coal forests, post-Jurassic land was moist and low-lying. It supported a rich vegetation (including coniferous trees and the palm-like *Cycads*) almost tropical in its character, and instead of the amphibia of Permian times numerous members of the great reptile Order Dinosauria were the dominant animals, although small and as yet unimportant representatives of the mammals were also in evidence.

Limestones in the Middle and Upper Oolites.—The Kellaways Rock, which is locally developed in the lower part of the Oxford Clay, includes beds of calcareous sandstone, but the rock is not used for any of the usual purposes of a limestone, although near Kellaways, and also near Scarborough (where it is thicker and represents a longer period of deposition) the rock was formerly quarried for roadstone. To this fact is due the wealth of fossils from the Kellaways Rock to be found in some of the older geological collections: in recent years the strata have rarely been exposed.

The Corallian beds, like most of the divisions of the Jurassic rocks, exhibit considerable lateral variations. They derive their name from the abundance of corals in certain divisions (*Fig.* 123); many of the corals appear to be in the position in which they grew, and form large masses resembling reefs. The general succession of strata may be summarised as follows:—

CORALLIAN BEDS

- *Upper Corallian Beds*, including clays and grits and the *Upper Calcareous Grit* of Yorkshire.
- *Coral Rag*, consisting of rubbly limestones with masses of coral.
- *Coralline Oolite*, represented by marls and limestones in the south, and a massive oolite in the north.
- *Middle Calcareous Grit*, a calcareous sandstone present in Yorkshire only.
- *Hambledon Oolite*, in Yorkshire only.
- *Lower Calcareous Grit*.

Good building stones are not abundant among the Corallian limestones, although the *Headington Stone*, which consists of broken molluscan shells and sea-urchins, was once extensively worked at Headington Hill near Oxford, and was used in many of the 18th and 19th century buildings in that city. It has, however, not worn well, and is not now quarried to any great extent. There are two varieties, a hard compact-looking grey limestone, used for plinths and steps, and a softer, somewhat cellular, earthy limestone used for walls.

Other Corallian limestones include the *Osmington Oolite*, of which some beds are oolitic and nodular. It is seen on the south coast between Ringstead and Osmington, and a yellowish brown oolitic variety has been quarried near Abbotsbury, especially for local use. *Marnhull Stone* is an impure well bedded oolite, *Calne Stone* is a coarse shelly oolite, and *Wheatley Stone* is a hard shelly limestone from Wheatley near Oxford.

In Yorkshire the Corallian beds are, to a large extent, siliceous, and include highly calcareous sandstones as well as limestones. *Hildenley Stone* is a fine-grained chalky looking limestone (probably the equivalent of the Coral-Rag of other localities), quarried at Hildenley near Malton and used locally with good results, as for example at Kirkham Abbey. The limestones of the Middle Calcareous Grit and the Lower Calcareous Grit have also been used in many of the localities where they occur.

The Portland Stone receives its name from the "Isle" of Portland (which is, however, really a peninsula) in Dorset, where there are extensive quarries in oolitic limestones. The Portland Beds include a sandy series below (Portland Sands), and a limestone series above (Portland Stone); the whole series is about 170 feet thick, of which the useful oolitic freestones constitute only about 20 feet. All the Portland limestones are of marine origin.

Among the fossils, molluscs are very abundant, including ammonites of enormous size (some are as much as two feet in diameter); corals are generally rare, but one form, *Isastræa oblonga,* is occasionally abundant.

The beds, like all shallow-water deposits, exhibit rapid lateral variations, and the useful limestones are not all on the same horizon. In the "Isle" of Portland there are four main divisions in the workable parts of the series:—

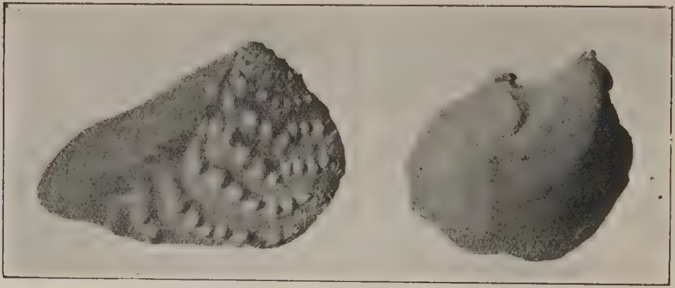

FIG. 125.—FOSSIL SHELLS FROM JURASSIC ROCKS.

On the left, the outer surface of *Trigonia irregularis* from the Oxford Clay of Weymouth, and on the right, a natural internal cast of the shell of *Trigonia gibbosa,* Sowerby, from the Portlandian Beds; half natural size.

PORTLAND STONE.

Roach (or Roche), a pale oolite, cavernous owing to the holes left by the removal of fossil shells such as the univalved mollusc *Cerithium* (Portland screws, *Fig.* 20) and the bivalve, *Trigonia* (see *Fig.* 125).

Whit Bed, a fine-grained oolitic freestone, pale brown when fresh, but weathering lighter on exposure, and from 4 to 15 feet in thickness.

Curf, a limestone with "flints" (really chert), and not of commercial value.

Base Bed (Best Bed, Bottom Bed or White Bed), a fine-grained pale oolite.

The Roach, from its cavernous nature, is not suitable for architectural work, but is used in heavy constructional work such as harbours, docks, and rough walls where high finish is not necessary. The cavernous character, although best developed in the Roach Bed, is sporadically developed at other levels also.

Both the Whit Bed and the Base Bed yield valuable freestones adapted for structural as well as ornamental work, but in the beds below the Base Bed, chert nodules are of too frequent occurrence for the rock to be extensively used; see *Fig.* 146 and p. 263.

The Whit Bed is very durable in exposed situations, but, having occasional layers of shells and sometimes exhibiting false bedding (*Fig.* 120), it is less suitable for fine carving and interior work than the more uniform Base Bed. The latter is mostly used for interior work, but some parts are suitable for exteriors if carefully selected [19].

The Portland Stone of Portland has been used for many centuries, and has found special favour in London. The intensive development of the quarries began in the early part of the 17th century when Inigo Jones, architect and surveyor to James I., recognised the value of the stone and used it in the Banqueting Hall (Whitehall). Its introduction to London is thus referred to in a contemporary poem (1622), by Henry Farley, a London freeman :—

> "Ere since the Architect of Heauen's fair frame
> Did make the World, and man to vse the same;
> In Earth's wide wombe, as in our nat'rall bed,
> We have beene hid, conceal'd, and covered,
> Where many thousand ships haue sailed by
> But knew vs not, and therefore let vs lye,
> Till at the last, and very lately too. . . .
> We were discouer'd, and to London sent,
> And by good Artists tryde incontinent;
> Who (finding vs in all things firme and sound,
> Fairer and greater than elsewhere are found)
> Did well approue our worth aboue them All
> Vnto the King for service at Whitehall" [20].

The poem was in the form of a booklet entitled, "*Portland Stone in Pauls Churchyard. Their birth, their Mirth, their Thankfulness and Advertisement, written by Hen. Farley, who hath done as freely for Freestone . . . as most men, and knows as much of their mindes as any man . . . to be sold at the great south door of Paules, London.*"

After the great fire of London, in 1666, Portland Stone was extensively used in rebuilding. Wren used it in St. Paul's Cathedral and in many of his churches, and for a time the Portland Quarries were, by the King's command, worked exclusively to supply stone for the Cathedral.

Other London buildings in which Portland Stone was used include the British Museum (1753) and Somerset House (1776) [21]. Smeaton used it in his Eddystone Lighthouse (1756) [22], and there are many examples of its use in important provincial buildings.

As examples of its modern use may be mentioned the façade of the new Waterloo Station, and the great building of Imperial Chemical Industries, Ltd., at Millbank, the exterior of which, apart from the ground-floor walls, is entirely of Portland Stone—

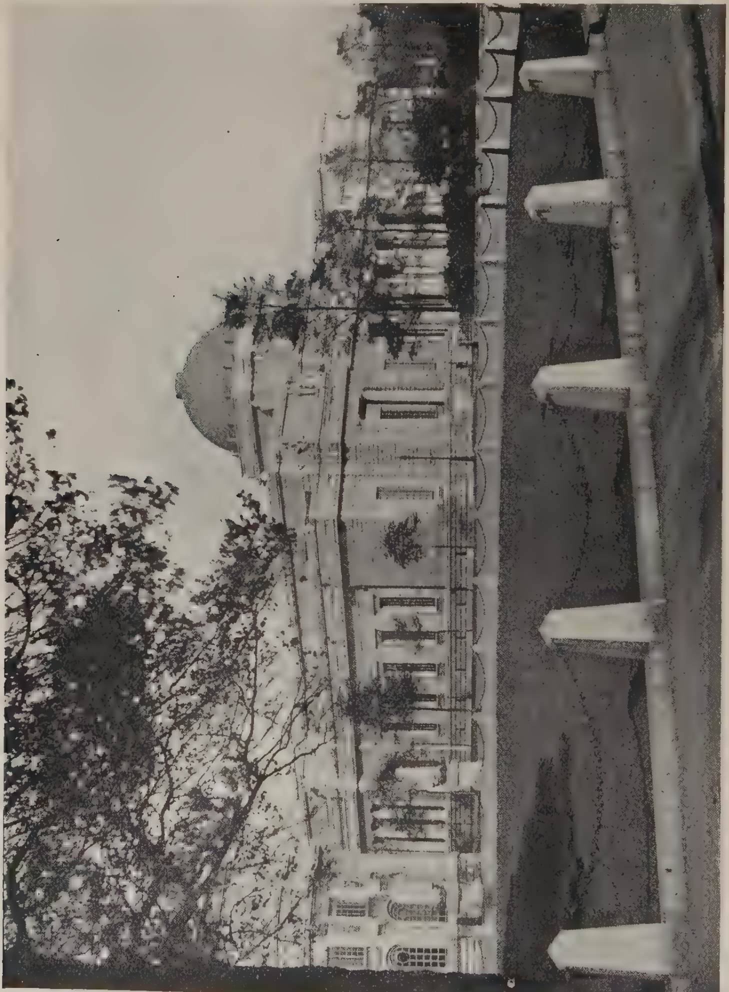

FIG. 126.—A MODERN BUILDING IN PORTLAND STONE.
(The National Museum of Wales, Cardiff.)

even the roof consists of slabs of that rock [23]. It is, indeed, essentially a limestone building, for marble and polished limestone (including Hopton Wood Stone and Purbeck Marble) are the principal materials used in the interior decoration. Vintry House, the imposing Thames-side building of the Vintners' Company, near Southwark Bridge, has also been faced, except in its lowest

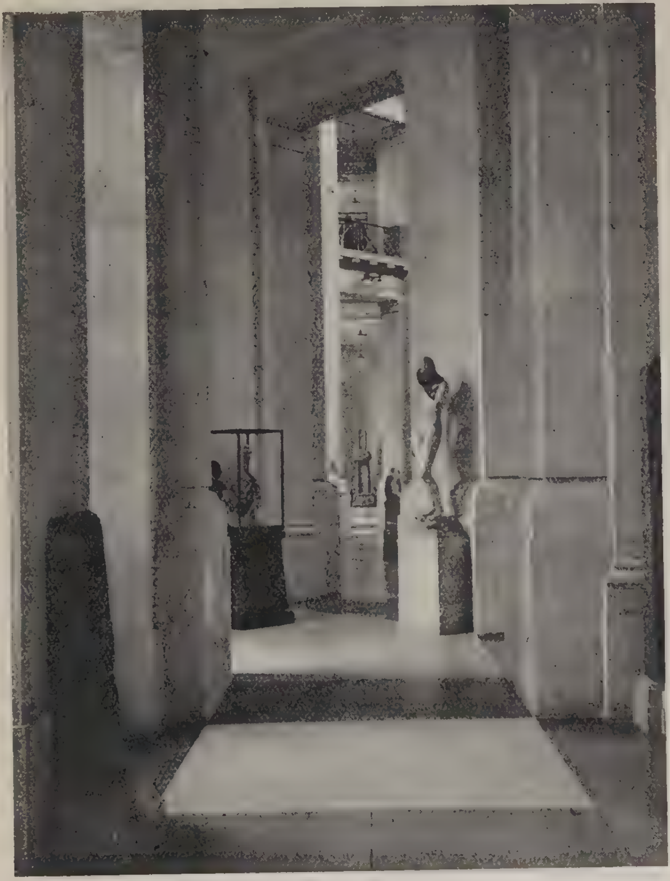

FIG. 127.—A LIMESTONE INTERIOR
(part of the Entrance Hall of the National Museum of Wales, Cardiff). The walls are of Portland Stone and the floor of "marble."

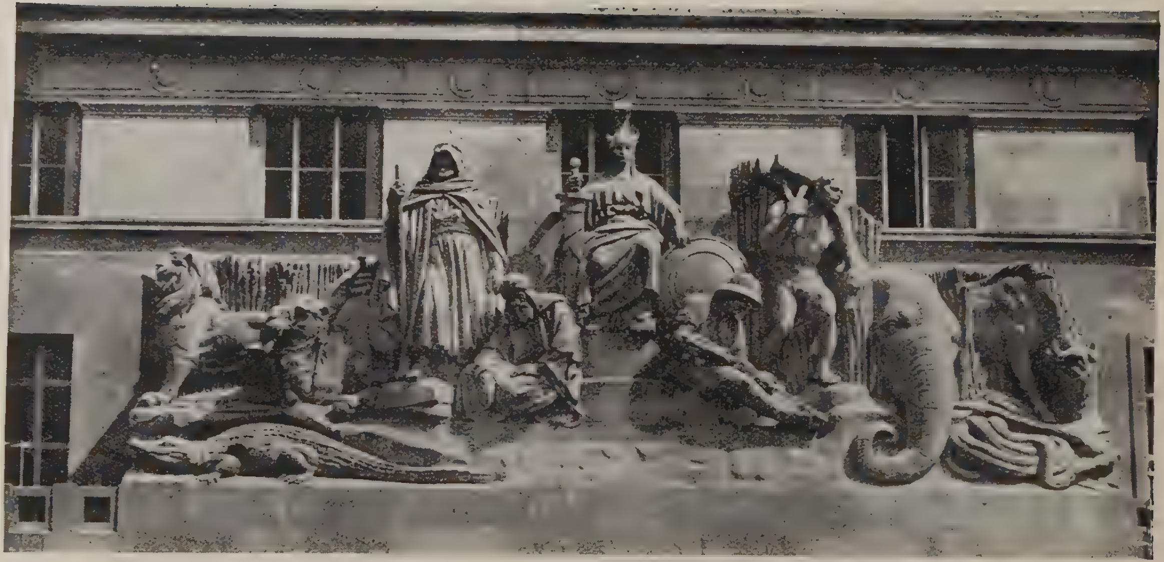

FIG. 128.—A GROUP OF STATUARY EXECUTED IN PORTLAND STONE (BY BENJAMIN CLEMENS) AT AFRICA HOUSE, KINGSWAY.

(Reproduced by courtesy of the editors of "The British Builder" and of "The Quarry.")

storey, with Portland Stone, and the same material played an important—perhaps the most important—part in the reconstruction of Regent Street [24], while in the provinces it may be seen, for example, in the group of public buildings in Cathays Park, Cardiff, of which the National Museum of Wales (*Figs.* 126 and 127) was the last to be erected.

An important characteristic of Portland Stone is that the best varieties are excellent freestones and can be carved for the decoration of buildings. A modern example of this application is seen in the great group of statuary by Benjamin Clemens, high up on the front of Africa House, Kingsway, London. It depicts some of the animals and natives of Africa with a British settler, grouped about Britannia who sits upon a throne.

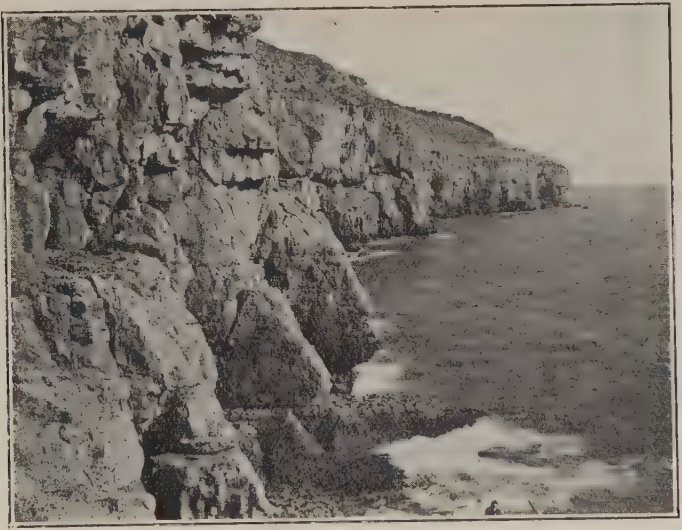

FIG. 129.—CLIFFS OF PORTLAND STONE.

Durlston Head, Dorsetshire: the cliff consists of Portland Stone capped by Lower Purbeck Beds. (Reproduced by permission of the Director of the Geological Survey.)

Building stones of Portland age are not confined to the Isle of Portland, but are found in other parts of the Portlandian outcrop. In the "Isle" of Purbeck, the Portland Beds are well exposed between Durlston Head and St. Albans Head; *Fig.* 129. Some of the oolites and freestones are quarried or mined, but although the quarries are nearly all on the coast, shipment of the stone is not easy except in calm weather. The Tilly Whim Caves near Swanage are old underground workings in one of the freestone beds; stone from this mine was used in building Corfe Castle. The Portland Stone of Purbeck (known commercially as Purbeck-Portland Stone) is harder and more compact than that of Portland. One variety, *Seacombe Stone,* is suitable for landings, steps, and in other situations for which the normal Portland Stone would be insufficiently hard.

When traced northwards, the Portland beds become thinner in the region of the area of Upper Jurassic uplift to which reference has already been made (page 224), and near Aylesbury they are replaced by clay (the *Hartwell Clay*), but in the intervening country the deposits are, on the whole, like those of Portland and are put to similar uses. The building stones are darker in colour and more siliceous than the Portland Stone of the coastal region. The silica occurs partly as sand grains and partly as a cementing material, but some is present in the form of the mineral glauconite, which is a complex silicate of iron and potash, and is responsible for the greenish tinge which is developed where the rocks are exposed to the weather. Most of the quarries are in the neighbourhood of the Vale of Wardour; the Chilmark, Wardour, and Tisbury Stones all come from this district, but are less worked now than in the past. They have been used in all parts of the country, and *Chilmark Stone* was used in the 13th century for building Salisbury Cathedral. The quarrymen have given names to the different varieties of stone obtained from the various quarries, but the names are mostly of local significance only and cannot be applied generally; see, however [25].

Strata of Portland age are exposed near Swindon; they include oolites and shelly limestones, but the thickest division, the "*Swindon Stone*" is a calcareous sandstone. In Oxfordshire, the Portlandian beds are more sandy than they are in the south, but some calcareous sandstones and shelly limestones have, from time to time, been quarried for building purposes around Shotover Hill, Thame, Aylesbury, and Brill.

The Purbeck Beds. — These strata derive their name from another peninsula—the so-called Isle of Purbeck in Dorsetshire (*Fig.* 130). They are thickest (about 400 feet) near Swanage, and, like the Portland Beds, thin out towards the north. The shore line of the sea in which the Portland Beds accumulated lay near Oxford, and with the progress of the uplift previously mentioned, the sea retreated to the south, so that by Purbeck times a good deal of Britain was dry land, with, in the south, a lake or an estuary into which large rivers discharged; the lake or estuary was the site on which the Purbeck beds accumulated. The rocks include thin beds of shelly limestone, separated by shales and marls, and are, for the most part, of freshwater or estuarine origin; there is one marine bed—called the *Cinder Bed* on account of its rough surface—which consists largely of oyster shells.

There are not many fossils in the Purbeck Beds, but certain freshwater snails (*Viviparus*, or *Paludina* of the earlier writers) sometimes built up extensive beds of limestone which constitute the once important Purbeck Marble (see *Fig.* 10). Insect and mammalian remains also occur. In the "Dirt Bed"—a land soil to which reference has already been made—there are the remains of cycads (palm-like plants) and coniferous trees. By the quarryman, the fossil cycad stumps are called Birds'-nests—which indeed they certainly resemble.

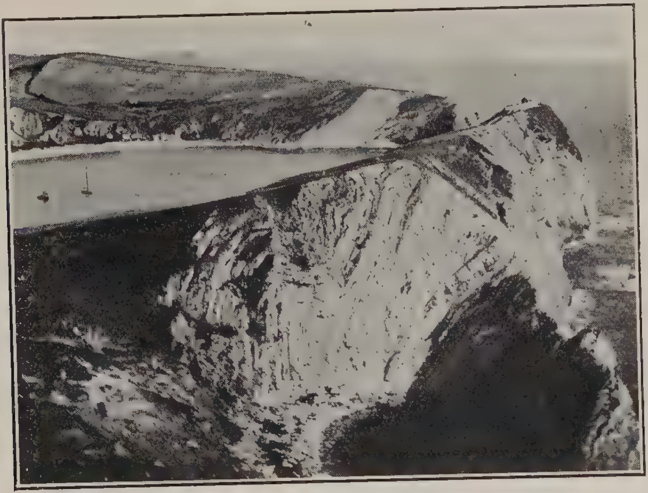

FIG. 130.—CLIFFS OF PURBECK AND PORTLAND LIMESTONES.
Lulworth Cove and Stair Hole, Dorsetshire. The contorted beds of Stair Hole in the foreground are of Lower and Middle Purbeck age. Portland beds appear in the base of the cliff under the flagstaff.

Limestones, consisting largely of estuarine shells, that occur in the middle part of the Purbeck Series are used for many purposes; they are referred to as *Purbeck Stone*, although the quarrymen have given names to each individual bed, and group the beds into "veins," of which the "Freestone Vein" is most used. The nature and extent of the local nomenclature will be realised from the fact that in about 49 feet of strata (including shales) the following limestone beds are recognised, commencing with that at the top. White Roach, Laming Vein, Royal, Red Rag, Rag, Under Rag, Top Shingle, Shingle, Upper Picking, Grub, Roach, Pink Bed, Grey Bed, Thornback, Freestone Bed, Blue Bed, Lias, Lias Rag, Laper, Under Picking, Upper Tombstone Bed, Brassy Bed, Lower Tombstone Bed.

Each of the various kinds has its own particular use; some are suitable for sea-walling and ordinary building work, others, of a slabby nature, for paving stones, roof-tiles, and tombstones. Stone from the harder beds is used for steps, kerbs, and gutters, and was at one time sent to London in large quantities for those purposes, while some beds yield stone for gate-posts, window-sills, sinks, and troughs.

The beds dip rather steeply and are thin, so that open quarrying is not usually possible and they are followed underground in shallow mines, of which there are scores in the hilly country south of Swanage and in the neighbourhood of Durlston Head. The mine is entered by a sloping shaft up which the stone is drawn by means of a horse-driven or donkey-driven windlass. The floor of the shaft is paved with stone for the passage of the trucks, and at the sides there are steps for the men, so that the methods employed in a Purbeck Stone mine are very similar to those in many mines, including coal mines, of four or five centuries ago.

At one time there were quarries along the coast of Durlston Bay; the stone beneath the desired beds was removed, props were inserted and left until they gave way, allowing a fall of rock to occur, after which suitable blocks were selected for use.

The *Purbeck Marble* is a greenish grey limestone crowded with freshwater shells, principally those of the univalve *Viviparus*, and it occurs in the Upper part of the Purbeck Series. It was used for decorative purposes by the Romans, having been found on sites they occupied at Silchester (north of Basingstoke in Hampshire), and Verulamium (near the present St. Albans), and in mediæval times it was one of the most highly esteemed of the ornamental stones then obtainable in this country. It was used in ecclesiastical buildings in all parts of the country — Wells Cathedral, York Minster, Ely Cathedral and Westminster Abbey —especially in the form of pillars and columns, either simple or clustered. Salisbury Cathedral (built in the early part of the 13th century) probably contains more Purbeck Marble than any other building, and in larger masses than were usually used. The pillars supporting the roof of the Lady Chapel, for example, are plain shafts, 30 feet high, each consisting of two 15 feet lengths. The reason for its lavish use in this particular building was that the owner (a lady named Brewer) of a quarry in the Isle of Purbeck, allowed Bishop Poore, the founder of the Cathedral, unrestricted and free use of her quarry for several years.

Purbeck Marble slowly went out of fashion and is now seldom used—one of the most recent buildings in which the " marble " plays an important part is Temple Church, London (1840). Various reasons are given in explanation of the decline in its use; it was possibly due to the somewhat sombre appearance of the rock as compared with the highly decorative foreign marbles that could, as transport facilities increased, be cheaply obtained. Although capable of taking a high polish, the smooth shining surface tends to become dim on exposure, and this, too, may have contributed to its replacement by other stones.

The antiquity of the stone industry in the Isle of Purbeck is indicated by the fact that the right to procure the stone is vested only in members of an old established guild, now called the " Company of Marblers and Stone-Cutters of the Isle of Purbeck "; the marblers have the right to open a quarry in any place where the stone occurs, except when the land is covered with growing corn; this privilege descends from father to son, and the quarrying community, which keeps itself as far as possible intact, may have descended from a colony of stone workers that came over in Norman times [25].

The Purbeck Beds are not confined to the Isle of Purbeck, but are similar in their distribution to the Portland Beds; at Upwey, near Weymouth, the lower division yields a good stone, and at Teffont Evias in the Vale of Wardour, some smooth-grained hard limestones are worked for local use as building stones. Strata of Purbeck age also occur in the south of Sussex, north of a line between Battle and Heathfield. The outcrop is narrow and discontinuous, and there are limestones at two horizons, namely, the " Greys," and the " Blues," which are 40 and 25 feet thick respectively, and consist of limestone beds associated with shales. The fossils indicate that most of the rock is of freshwater origin, although beds with marine fossils occasionally occur. The rock has in the past been used for lime-burning and for paving slabs, and will be further mentioned in a subsequent chapter when the history of the use of limestone is being discussed [26].

Other commercial uses of the Jurassic limestones.—In the foregoing notes, reference has been made only to the use of the Jurassic limestones as building and ornamental stones, except in the case of the Lias, for it is as building stones that they are best known and most widely used, but it is necessary to bear in mind that many of the rocks are suitable for the other uses (such as lime-burning and road-making) to which limestones may be put [27]; see Additional Note, page 449.

The purer limestones of all horizons have been or still are burnt for lime. This is the case for example with the Inferior Oolite in the West of England; while in the Great Oolite of the south midland region, where some of the layers are marly, the various beds are mixed and a good strong lime is produced. The Fuller's Earth Rock has been burnt for lime (building lime) near Sherborne, but the lime from the Forest Marble is, as a rule, less suitable for mortar than is that from the Cornbrash which has been extensively burnt in Dorsetshire, near Bedford, and near Peterborough. In the south, the Portland and Purbeck limestones are burnt for lime, and in Yorkshire, it is made from various beds in the Upper Corallian Limestone. Hydraulic lime resembling that derived from Liassic limestone is obtained from some of the lower beds of the Lincolnshire limestone.

Most of the Jurassic limestones are too soft to be used as roadstones, except locally on by-roads, but some of the beds of the Great Oolite (*Dagham Stone* from near Cirencester) Forest Marble, Cornbrash, Coral Rag, Calcareous Grit, and the Grey Limestone of Yorkshire are used for roadmaking.

The former extension of the Jurassic Rocks. — The western limit of the main Jurassic outcrop has, as we have already seen, been determined by denudation, but that the rocks were laid down over a much wider area than they now occupy is indicated by the small outlying patches that occur in the west of England, in Scotland, and in Ireland. Limestones play a comparatively small part in those outliers, the interest of which in the present discussion lies principally in the light they throw upon the geography of the time of their accumulation (see *Fig.* 131).

There are small outliers of Lias in Shropshire and near Carlisle, and strata of that age are well represented in Skye and other islands of the Inner Hebrides and also on the adjacent Scottish mainland, where they are mostly sands and conglomerates that must have been deposited near the margin of the sea. Similar rocks also occur beneath the Chalk of north-eastern Ireland, and in the Isle of Arran some fossiliferous Liassic rocks have been found in the neck of a volcano that was active during the early part of the Tertiary period [28, 29]. The material, which had evidently been disturbed during an eruption and had fallen into a crater, indicates that, although for the most part removed by denudation, some of the Mesozoic strata remained in the district as least until early Tertiary times.

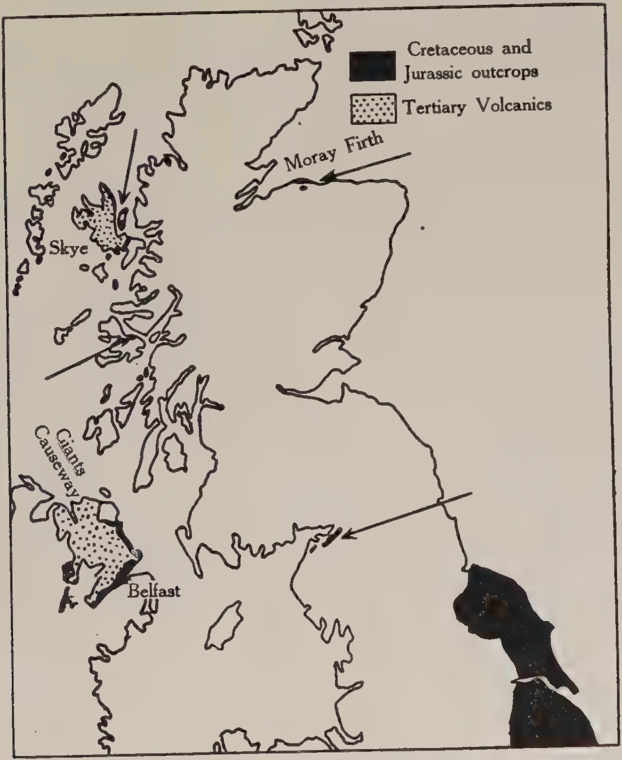
Cretaceous and Jurassic outcrops
Tertiary Volcanics
Moray Firth
Skye
Giants Causeway
Belfast

FIG. 131.—MAP ILLUSTRATING THE NORTHERN AND WESTERN OUTCROPS OF THE JURASSIC AND CRETACEOUS ROCKS, AND THEIR RELATION TO THE IGNEOUS ROCKS OF TERTIARY AGE.

In the Island of Raasay the Liassic beds include an oolitic ironstone about eight feet thick, resembling those occurring in Yorkshire, and limestones of Lower Liassic age at Loch Aline, Argyllshire, have been burnt for lime [30]; the Lias is also represented on the east coast of Scotland, in Sutherlandshire.

The Oolitic strata that have been preserved in Scotland also indicate that the margin of the later Jurassic sea was not far away. On the west coast and in some of the Hebrides the Inferior Oolite is represented by sandstones and shales with a thin shelly limestone, and the Great Oolite by estuarine shales with thin freshwater limestones. On the eastern coast, at Brora in Sutherland, there are strata, probably of Great Oolite age, that comprise sandstones and shales with thin limestones and some coal seams.

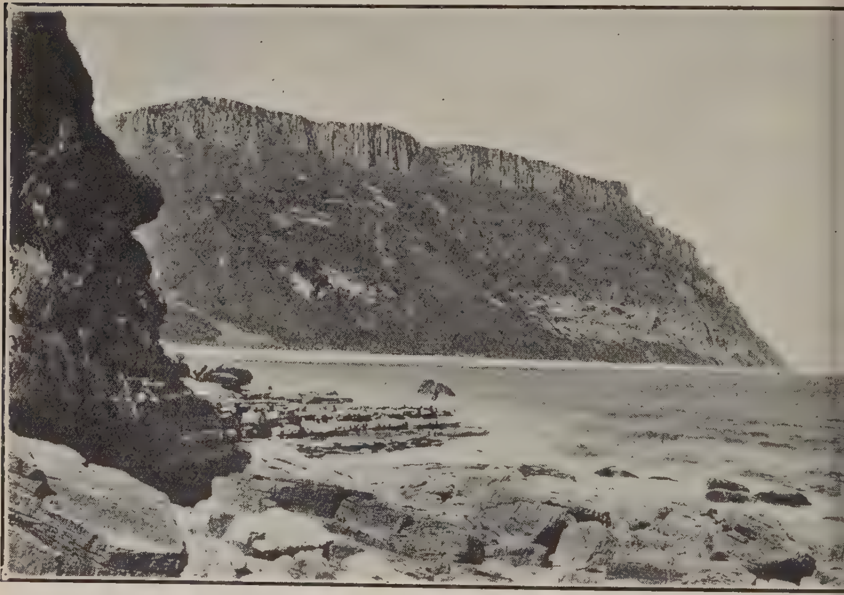

FIG. 132.—CLIFFS AT BEARRERAIG, SKYE.

The main part of the cliff is Inferior Oolite, and it is capped by a "sill" o basalt with columnar structure. (Reproduced by permission of the Director of the Geological Survey.)

The Oxford Clay is represented on the west coast by clays with beds of argillaceous limestone, and in Sutherland by shales with calcareous sandstones: in the latter region there are representatives of both Corallian and Kimmeridge beds (clays, sandstones, and limestones, partly of marine origin and partly estuarine) but no strata later than the Oxford Clay are preserved on the west coast of Scotland. The preservation of the Jurassic rocks on the west coast of Scotland is to a large extent due to the protection afforded by the lavas of Tertiary age to which reference will be made at a later stage (see *Fig.* 132).

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32. 1914—Johnson, A. H., "History of the Company of Drapers," p. 304.

33. 1905—Geikie, A., "The Founders of Geology," 2nd edition, p. 322, Macmillan & Co., London.

The following are among the many works in which the fossils of the Oolites are described; each of them will be found to contain further references to the branch of the subject to which they relate:—

34. 1865-70—Phillips, J., "British Belemnitidæ," *Monograph, Palæontographical Society* (London).

35. 1887-96—Hudleston, W. H., "The British Jurassic Gasteropoda," *Monograph, Palæontographical Society* (London).

36. 1851-63—Morris, J. & J. Lycett, "The Mollusca from the Great Oolite," *Monograph, Palæontographical Society* (London).

37. 1872-79—Lycett, J., "British Trigoniæ," *Monograph, Palæontographical Society* (London).

38. 1905-7—Blake, J. F., "The Fauna of the Cornbrash," *Monograph, Palæontographical Society* (London).

39. 1851-78—Davidson, T., "British Fossil Brachiopoda, Oolitic and Liassic Species," 1851; Supplement, 1876-78, *Monograph, Palæontographical Society* (London).

40. 1857-80—Wright, T., "The British Fossil Echinodermata of the Oolitic Formations," *Monograph, Palæontographical Society* (London).

41. 1887-1907—Buckman, S. S., "The Inferior Oolite Ammonites of the British Islands," *Monograph, Palæontographical Society* (London).

42. 1909-28—Buckman, S. S., "Yorkshire Type Ammonites," Vols. 1 and 2, continued as "Type Ammonites," Vols. 3 to 6, London.

43. 1898—Crick, G. C., "Species of Nautilus from the Inferior Oolite," *Proceedings Malacological Society*, Vol. 3, pp. 117-139.

44. 1860—Buckman, J., "On some Fossil Reptilian Eggs from the Great Oolite of Cirencester," *Quarterly Journal Geological Society* (London), Vol. 16, pp. 107-110.

45. 1871—Carruthers, W., "On some Supposed Vegetable Fossils," *Quarterly Journal Geological Society*, Vol. 27, pp. 446-7.

CHAPTER XI.

LIMESTONE IN THE CRETACEOUS SYSTEM OF ROCKS.

> Now comes a time, when through the land and sea
> Great change is wrought, all slowly though it be . . .
> Lower and lower the sinking lands subside,
> Deepening the mighty waters far and wide;
> Till lands, that in Jurassic days were dry,
> Beneath the brine some scores of fathoms lie.
>
> H. R. Knipe, in "*Nebula to Man*" (1905).

Geographical conditions at the close of the Jurassic Period.—It has been shown (*a*) that in the British region the Jurassic period commenced with the return of the sea to a district that had for a long time experienced continental conditions, and (*b*) that the Jurassic rocks were laid down in a more or less enclosed sea, the limits and depth of which varied from time to time. The restricted distribution of the latest Jurassic deposits (the Portland and Purbeck beds of the south and the Speeton Clay of the north) shows that earth-movements — of which there had been premonitory signs during the earlier Oolitic times — were taking place, and were resulting in the uplift of the central tract of the Jurassic sea. This movement continued into the earlier part of the succeeding Cretaceous Period, with the result that while in the north and in the south there is a transition from Jurassic strata to those of Cretaceous age, in the midland region a considerable thickness of strata is missing, and the rocks of the two systems are separated by an unconformity.

At the close of the Jurassic period marine conditions prevailed in the north (for example, Yorkshire), but freshwater and even land conditions had been established in the south; in consequence, while the lower part of the marine Speeton Clay of the north is of Jurassic age (corresponding to the Portland and Purbeck Beds) and its upper part is of Cretaceous age, in the south, the freshwater and estuarine Purbeck (Jurassic) Beds are succeeded by the (Cretaceous) Wealden Beds, which are very similar in general character.

The Cretaceous System.—Like those of the Jurassic System, the Cretaceous rocks of England have a general easterly or south-easterly dip, and they extend as a broad curved band from Yorkshire to Dorsetshire, with east to west extensions from the neighbourhood of Salisbury Plain to the coasts of Kent and Sussex; *Fig.* 133. As in the case of the Jurassic rocks, the Cretaceous outcrop has lost much by denudation, for the strata once extended much farther to the west and north than they do at the present time. There are small outlying patches in Devonshire, while in Mull,

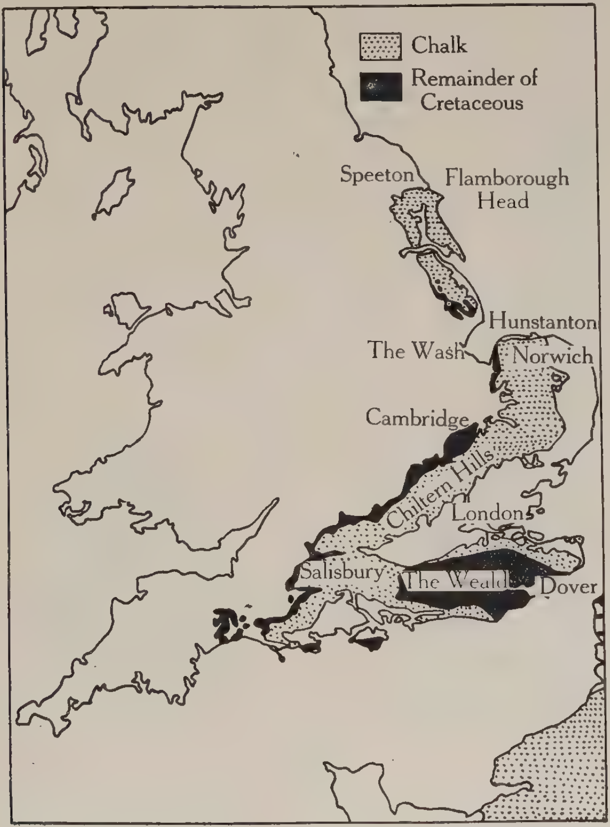
▨ Chalk
■ Remainder of Cretaceous
Speeton
Flamborough Head
Hunstanton
The Wash
Norwich
Cambridge
Chiltern Hills
London
Salisbury
The Weald
Dover

FIG. 133.—MAP ILLUSTRATING THE DISTRIBUTION OF THE CRETACEOUS ROCKS IN ENGLAND AND WALES.

the adjacent Scottish mainland, and in northern Ireland, Cretaceous rocks are associated with the Jurassic beds that have been preserved beneath the Tertiary lavas.

A simple classification of the English Cretaceous rocks is as follows :—

	In the South.	*In the North.*
Upper Cretaceous	Chalk (and Upper Greensand)	Chalk
	Gault	Red Chalk
Lower Cretaceous	Lower Greensand	——
	Wealden Beds	Speeton Clay (Upper Part)

The life of the Cretaceous Period.—Many forms of life continued from the Jurassic Period into the Cretaceous, but by the time the Chalk was being deposited the Cretaceous fauna had taken on a character of its own, although in comparing the fossils of the Chalk with those of the Oolites, for example, it is necessary to take into consideration not only the differences between the ages of the two sets of strata, but also the great difference between the conditions under which they accumulated : this matter will be discussed later in connection with the chalk.

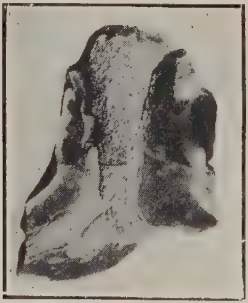

FIG. 134.—FOSSIL SPONGE IN A CHALK FLINT ; natural size.

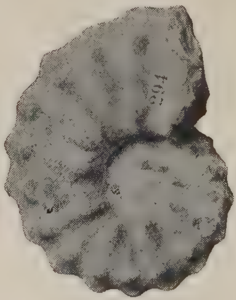

FIG. 135.—A CHALK AMMONITE. *Acanthoceras rhotomagense*, Brongniart, from the Lower Chalk ; about natural size.

In the Cretaceous rocks, sponges are particularly important (*Fig.* 134), but corals are rare, although a few simple conical forms occur in the Chalk, in which the microscopic shells of the simple animals known as foraminifera are also abundant. All divisions of the mollusca are represented: gastropods are not as abundant as they became during the succeeding Tertiary periods, and ammonites (*Fig.* 135) are neither as common nor as varied as in the Jurassic rocks, although belemnites (*Fig.* 136) are important in some parts of the Chalk; freshwater bivalves (*Unio*) are present in the Wealden Beds, and a few kinds of bivalves are fairly common in the marine strata.

Among the most characteristic fossils of the Chalk are the echinoids or sea-urchins, which are varied and abundant: some of them, which show progressive changes as they are traced from bed to bed, have been used in dividing the rock into zones; see page 132. The crinoids or sea-lilies, which were so important in the Carboniferous Limestone and in certain beds of the Lias, are also represented. Brachiopods are less numerous than in the Jurassic strata, but the genera *Terebratula* and *Rhynchonella* are important, and there are numerous genera of polyzoa.

All the foregoing invertebrate groups contributed to the formation of limestone when the conditions of sedimentation were favourable. Fish remains (bones and teeth) are abundant, especially in the Chalk, and reptiles are also represented, both marine forms and land forms (such as the dinosaur *Iguanodon*) being known. Primitive toothed birds occur, but no mammals have as yet been recorded in the English Cretaceous strata.

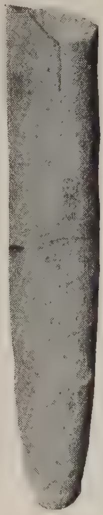

FIG. 136.—A CHALK BELEMNITE.

Belemnitella mucronata (Schlotheim) from the Upper Chalk; about natural size.

The Lower Cretaceous Rocks. — The Wealden Beds were deposited in a series of lakes or lagoons that occupied approximately the area over which the Purbeck Beds were laid down, and they extend from Dorsetshire through the south-eastern counties, and for an unknown distance into the south-east of France. Limestones are not important except at one horizon, and the series does not, therefore, call for special comment here; a simple classification of the beds is as follows:—

WEALD CLAY.

Clays and shales with a few thin bands of limestone containing freshwater snails: in the Isle of Wight there are quantities of fossil wood.

HASTINGS SAND GROUP.

Tunbridge Wells Sand—an unfossiliferous sandy series, often highly charged with iron.

Wadhurst Clay—named from the village of that name near Tunbridge Wells—consisting mainly of clay, but including bands of freshwater limestone (*Sussex Marble*) with the shells of the water-snail *Viviparus.* Towards the base there are nodules and bands of ironstone which were at one time of great importance as a source of iron, and the division also includes the *Tilgate Stone,* a calcareous sandstone that has yielded important reptilian remains.

Ashdown Sands—sandstones, some of them quite soft, and, although not yet exploited to any extent, probably of great value; the *Fairlight Clay* occurs locally at the base and contains plant remains.

This classification holds good only in the Wealden district; further west and north the upper divisions, at least, lose their identity.

The *Sussex Marble* is a greenish grey rock crowded with the shells of a large species of *Viviparus*; in appearance it bears some resemblance to the Purbeck Marble, and, being capable of taking a high polish it has been used for decorative work under the name Sussex Marble or *Bethersden Marble.* It is seen in many of the early Perpendicular churches of the district, and also in the altar steps of Canterbury Cathedral: near Grinstead it has been used for ordinary building purposes.

The Speeton Clay Series. — This group of beds, which in Yorkshire and Lincolnshire represent the strata between the Kimmeridge Clay and the lower part of the Chalk, is essentially a series of marine clays, marls, and sandstones, and it does not include many important limestones.

In Lincolnshire there is, in the upper part of the series, a thin shelly limestone (the *Tealby Limestone*), and both in Yorkshire and Lincolnshire the top of the Speeton clay is characterised by the *Red Chalk* which represents, in part at least, the Gault of the southern counties, and will be described later.

The Lower Greensand.—In the earliest Cretaceous times there were two areas of deposition, one in the north (marine) and another in the south (largely freshwater), but the ridge separating them was submerged, at least temporarily, during Lower Greensand times, for deposits of that age occur (somewhat irregular in distribution and in thickness) all the way from the south coast to Yorkshire.

The name "Greensand" is not very appropriate because although there are greenish coloured sands, many of the sandy divisions are not green and the group includes much clay.

In the Wealden district of Kent, Surrey, and Sussex, the succession of strata included in the Lower Greensand Series is as follows:—

Lower Greensand Series.	*Folkestone Beds*—light coloured unfossiliferous sands with irregularly developed calcareous sandstones.
	Sandgate Beds—greenish clays.
	Hythe Beds—greenish sandstones, with sandy limestones (*Kentish Rag*).
	Atherfield Clay — sandy clays, sometimes fossiliferous.

There is, at the base of the Atherfield Clay in the Isle of Wight, a bed containing fragments of bone and small pebbles, resembling the "Bone Bed" at the base of the Rhætic Formation, and due, no doubt, to a similar cause, namely, the invasion by the sea of an old lake (that in which the Purbeck Beds accumulated).

In the midland region the Lower Greensand Series is represented by areas of sand and gravel, often fossiliferous, resting on rocks belonging to various divisions of the Jurassic System, but there are no limestones of any importance.

Kentish Rag.—The Kentish Rag which occurs in the Hythe Beds of the Wealden area is an important building stone. Over much of the region where they occur the Hythe Beds consist of thin beds of limestone alternating with soft calcareous sandstones—the former are called *Rag* and the latter *Hassock*. The Hassock is usually soft but it is occasionally hard enough to be used for building purposes; under the name *Calkstone* it is used for lining walls constructed of Rag. The Rag is variable; it may contain as much as ninety per cent. of calcium carbonate, or it may be very sandy: the sandy varieties frequently pass into rocks of the "Hassock" type. Kentish Rag is impervious to water, and is grey or greenish grey in colour; it is more suitable for outer walls than for interior use, because, being hard and very tough it is difficult to dress, and on account of its impermeability it does not readily absorb moisture, which tends to condense upon its surface, giving rise to "sweating." Kentish Rag has been used continuously since the days when the Romans employed it in the walls of London. Rochester Castle (1078) was built largely with the stone, and in the records of the expenses incurred in connection with the Tower of London there are entries such as "one boatload of Aylesford Stone called rag, 6s." According to Sir Christopher Wren, each of the three Cathedrals erected on the site of the London St. Paul's that was destroyed in the fire of 1666 had been placed on old foundations of Kentish Rag: in conjunction with Bath Stone it was much used in London houses during the early part of the last century [1].

There are important quarries in the Kentish Rag near Maidstone, where, in about 25 feet of strata, there are several beds of Rag alternating with beds of Hassock, and underlain by beds of "Blue rag" or "Hoisting," which makes excellent roadstone.

Also of Lower Greensand age is the *Bargate Stone* of Godalming. It is variable in character, and one variety is a greyish compact sandy limestone, with 70 per cent. of calcium carbonate, strongly resembling the Kentish Rag; other varieties are rubbly and argillaceous, or are pebbly, but the cementing material is always calcareous.

The Upper Cretaceous Rocks. — The ridge, which in later Jurassic and earliest Cretaceous times separated a northern from a southern area of deposition, was completely submerged as the Cretaceous period drew to a close, the Gault being the earliest Cretaceous deposit to be laid down over the whole of the site of the old land area that lay to the north of the basin in which the Purbeck and Wealden beds accumulated. At first, even when both were marine, there was a great difference between the deposits in the two areas, for while in the south the sediments were mainly dark clays (Gault), in the north, highly ferruginous limestone (Red Chalk) was laid down; but by Chalk times subsidence had proceeded sufficiently far for the sea to have extended like a great "Mediterranean Sea" from Ireland to Russia; the result is that the Upper Cretaceous rocks, being laid down in a more extensive and deeper sea, are much more uniform in character than those immediately underlying them.

In this country, the Upper Cretaceous rocks are mainly sandy and argillaceous in their lower part, and calcareous in their upper part.

The succession is as follows:—

The Chalk.

	Lithological Divisions.	*Time Divisions.*
Upper Cretaceous Series.	——	Danian
	Upper Chalk	Senonian
	Middle Chalk	Turonian
	Lower Chalk	Cenomanian
	Upper Greensand and Gault	Albian

The names in the right hand column are those applied, first by French geologists, in order to overcome difficulties of classification due to local variations in the lithological characters of the rocks: the divisions depend, like the zones of the Carboniferous Limestone, upon the evidence of fossils, and they are, therefore, of much wider application than names (such as Chalk) which are based on lithological characters. The Danian Beds, so called from their development in Denmark, are not present in this country.

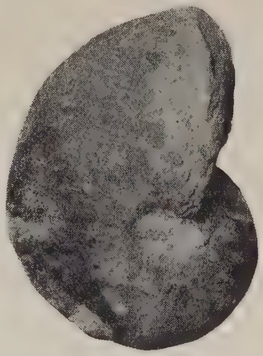

FIG. 137.—A CEPHALOPOD. *Nautilus albensis*, d'Orbigny, from the Red Chalk of Hunstanton, Norfolk.

Gault and Upper Greensand. — In this country, the deposits of Albian age consist mostly of stiff blue clays (Gault) in the south-eastern district, and in the southern part of the midlands, but locally, the upper part of the division is sandy—the so-called Upper Greensand. In Devonshire and Dorsetshire the whole series is sandy, but in Yorkshire and the neighbourhood of the Wash, the deposits, as we have already seen, belong to a totally different area of deposition. Here the lower part is argillaceous (part of the Speeton Clay) but the upper portion is calcareous and includes the "Red Chalk," which is the only limestone of Albian age in this country.

The Red Chalk.—At Hunstanton, the Red Chalk (a brick-red chalky limestone with large grains of quartz) is about three feet thick and it contains many fossils which are characteristic of the Gault of the south (*Fig.* 137): traced northwards through Lincolnshire it sometimes reaches 10 to 12 feet, while near Speeton, in

Yorkshire, the series becomes very much thicker and includes marls and clays as well as irregular layers of red chalk.

The Red Chalk has been used locally for building purposes: it has never been quarried, but blocks distributed on the beach as a result of cliff erosion at Hunstanton have been gathered from time to time.

The Chalk.—As applied to a rock, the term chalk usually connotes a soft, earthy, light-coloured and very pure limestone, but "The Chalk," in the stratigraphical sense, includes some rocks that are hard and marly and others that are sandy, although on the whole the variations are not very obvious to the casual observer. The geological conditions under which it accumulated will be discussed later in connection with the general question of the origin of chalk.

In the south of England the following divisions can be recognised:—

The Chalk	*Upper Chalk*—white chalk, with many flints. *Middle Chalk*—white chalk, with few flints and occasional marls, passing down into hard nodular chalk (*Melbourn Rock*). *Lower Chalk*—marl, with massive white chalk in the upper part, *Grey chalk*, with the "*Chalk Marl*" and "*Chloritic Marl*" in the lower part.

The colour of the chalk is, to some extent, an indication of its purity: all varieties, when microscopically examined, are found to contain minute fragments of various minerals, including quartz, felspar and hornblende, but while the proportion of such non-calcareous matter may be as low as one per cent. or even less in the white Upper Chalk, it may rise to 40 per cent. in the Chalk Marl and 44 per cent. in the Grey Chalk.

Towards the west, the Chalk, like the Gault, becomes sandy, especially in its lower part, and in Devonshire the Lower Chalk is represented by a calcareous sandstone. In the central region of England, the Upper and Middle Chalks are generally like the corresponding rocks of the south, but the Lower Chalk includes an important shelly rock—the *Totternhoe Stone*—and has as its base a deposit of sand and pebbles with nodules of phosphatic material (the *Cambridge Greensand*).

From Norfolk to Flamborough Head the character and thickness of the various divisions undergo a change. The Lower Chalk is not so argillaceous as in the south, the Middle Chalk contains more flints, and the Melbourn Rock is not separately distinguishable, while the Upper Chalk is not only much thicker than it is in other districts, attaining to over 1,000 feet in Norfolk, but it includes beds that are higher in the sequence than any others that occur in this country.

The White Chalk gives rise to open country and rolling downs (*Fig.* 138): the soil is normally thin and supports a short springy turf, but during the process of weathering, insoluble material left after the removal of the calcareous matter may remain as a superficial layer, variable in thickness and distribution, forming the *Clay-with-Flints*, patches of which are often covered with woodland or are cultivated.

The Chalk in industry.—In the British Isles the chalk occupies a larger area than any other limestone formation, excepting the Carboniferous Limestone, and its industrial importance may be gauged from the fact that it constitutes nearly one third of the calcareous rock that is quarried, while a recent Home Office list gives particulars of over 200 chalk quarries. Nearly half the total output is derived from Kent, the next largest producers being Essex, Yorkshire, and Bedfordshire.

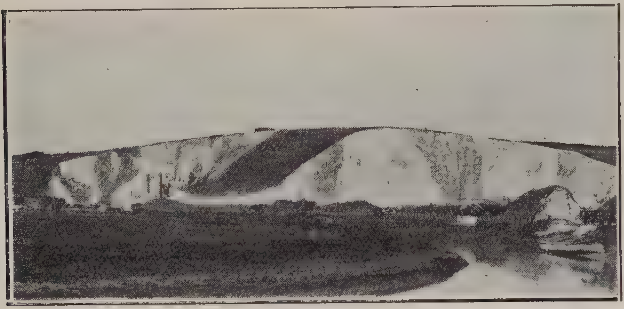

FIG. 138.—CHALK QUARRIES, NEAR LEWES, SUSSEX.

The photograph shows the open nature of the chalk country, and two quarries in the Upper Chalk that are worked largely for lime. (Reproduced by permission of the Director of the Geological Survey and the Controller of H.M. Stationery Office.)

By far the greater proportion of the output is utilised in lime-kilns and in cement manufacture; *Fig.* 139. For lime-burning the purer limestones of the White Chalk are most suitable, but the more argillaceous character of beds of the Middle and Lower

Chalk does not detract from their value for the purposes of cement making. In Kent there are important cement works along the Thames and the Medway, using chalk and either clay from the Gault or mud dredged from the river bed, while in other places, for example, Chinnor, in Oxfordshire, a mixture of Chalk and the highly argillaceous Chalk Marl is found to give good results: the manufacture of cement has already been mentioned in connection with the Lias (see also page 189), and the process is essentially the same whatever the nature of the calcareous and argillaceous ingredients that are used.

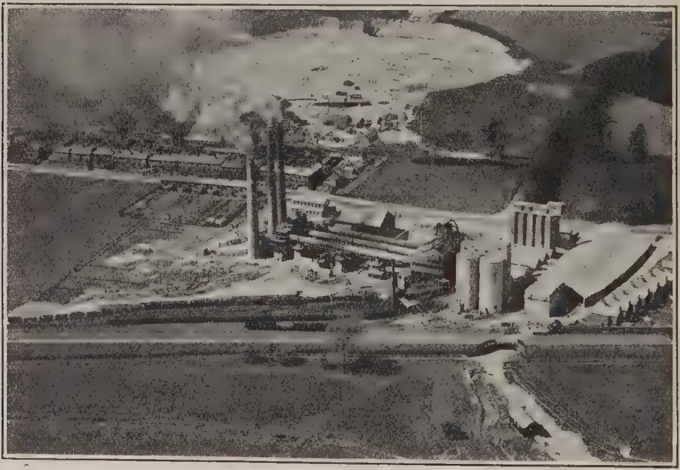

FIG. 139.—A CHALK QUARRY AND A CEMENT WORKS.

Holborough, Kent; reproduced by courtesy of the Holborough Cement Works.

Except for certain local varieties, such as those mentioned below, chalk has not been extensively used as a building stone on account of its softness and its poor resistance to weathering: instances of its employment will be found in many of the memoirs of the Geological Survey that relate to districts where chalk occurs [*e.g.*, 2, 2a].

Boynton Stone, from the Upper Chalk of Boynton, near Bridlington, in Yorkshire, has been used locally for building, but elsewhere most of the chalk building stone has been obtained from the Middle and Lower divisions. In Cambridge, Norfolk and the entral region of the outcrop, and in Kent, chalk has been used or cottage buildings, usually with inner and outer walls of quared blocks and the spaces between filled with rubble.

At Amberley, in Sussex, there is a chalk freestone—a dis- inctive white rock obtainable in large blocks—that has been used n vaulted ceilings in Arundel Castle, Chichester Cathedral, and ther buildings.

Totternhoe Stone is a local variety of the Lower Chalk which akes its name from Totternhoe, near Dunstable, in Bedfordshire, where it is quarried. It is a granular rock, greenish grey in colour, and harsher to the feel than most varieties of chalk because it consists largely of minute fragments of shells, especially those of the bivalve *Inoceramus*. The thickness varies from a maximum of about 17 feet near Totternhoe to as little as 6 feet in Buckinghamshire.

Totternhoe stone is soft when first quarried, and although it hardens on exposure, it is not suitable for outside carved work, being better adapted for interiors and vaulted roofs, as may be seen in St. Albans Abbey, parts of Windsor Castle, and in numerous Bedfordshire, Buckinghamshire and Hertfordshire churches [3]. Near Totternhoe itself the rock was formerly obtained from underground tunnels or mines, but in recent years the overlying beds that were not suitable for building purposes have been quarried for lime-burning. A marly chalk found near Burwell, Cambridgeshire, at about the horizon of the Totternhoe Stone, has been used for building purposes.

Similar to the Totternhoe Stone is the Clunch or *Clunch Rock*, which is also part of the Lower Chalk of Cambridgeshire. Clunch was used locally for building purposes as far back as the time of the Romans, and it was also used in many of the early Cambridge colleges: being easy to carve, it was found suitable for decorative work, as in parts of Ely Cathedral. Quarrymen and builders often describe as "clunch" all the varieties of chalk that can be used for building, but the name should really be used for the marly types such as occur in the Chalk Marl.

One of the most interesting of the chalk building stones is the *Beer Stone* from near Axminster, in Devonshire. It occurs in the lower part of the Middle Chalk, and is cream coloured or nearly white: it consists of minute fragments of many kinds of shells, cemented in a calcareous matrix that is largely crystalline, and it is, in consequence, a strong stone, its crushing strength being similar to that of Portland stone. The rock is soft and easily quarried when fresh, but it hardens considerably on exposure.

The quarries near Beer have been worked since the time of the Romans, and the rock (the best beds of which are together about 12 feet thick) is now worked by means of levels driven into the hillside: it is obtainable in comparatively large blocks.

Beer stone, like many of the geologically young limestones, is most suitable for interior work, and, like Totternhoe Stone, has been largely used in vaulted ceilings, principally on account of its lightness: for example, the weight of a cubic foot of Beer Stone is 131.7 lbs., of Portland Stone 137 lbs., and of a typical Carboniferous Limestone 158 lbs. It has been used in practically all parts of the south of England, and St. Stephen's Crypt, in the Houses of Parliament, affords an example in a building of historic importance; see Additional Note, page 449.

There is an interesting record relating to the cost of Beer Stone during the 14th century (1366-1367) in the Exchequer accounts relating to the building of Rochester Castle, for which, among other stones, 55 tons of Beer Freestone were purchased at from 9s. to 10s. a ton: for the same building there were imported 62 tons of Caen Stone at 9s. a ton, and 1,850 tons of rag stone from Maidstone at 40s. for 100 tons [4].

Cretaceous limestones, some of them chalky and others shaly, occur and are extensively used in various parts of Europe (Denmark, France, Austria), but in Silesia and Saxony, the Upper Cretaceous beds are mainly sandstones of considerable commercial importance.

Cretaceous rocks of Scotland and Ireland.—We have already seen (*a*) that the Upper Oolitic and the Lower Cretaceous rocks were deposited in restricted areas on account of the elevatory movement that had caused a steady diminution in the extent of the Jurassic sea, and (*b*) that a downward movement which had commenced early in Cretaceous times had so far progressed by Gault times that the central region of England was again submerged. The depression and consequent encroachment of the sea continued, but did not involve Scotland and Ireland until well into Cretaceous times, because the only Cretaceous rocks that were deposited in those regions belong to the latter part of the period; they are of Upper Cretaceous age.

In Northern Ireland (Antrim) the Cretaceous rocks rest directly on beds of Triassic and Liassic age; the lower part consists of marls and sandstones proved by their fossils to be the equivalents of the Lower Chalk (and perhaps of the Upper Greensand also) of England, while the upper part consists of hard chalk with flints, representing the Upper Chalk; the Middle Chalk appears to be absent, and the upper and lower divisions are separated by an unconformity. The chalk is quarried at a number of places in Antrim.

On the Island of Mull and the adjacent parts of the Scottish mainland, Cretaceous rocks, generally similar to those of Ireland, occur; they include sands and hard chalk, but some of the upper beds contain much lignite and may perhaps be of estuarine origin.

Both in Scotland and Ireland the Cretaceous beds occur beneath the great basaltic lava flows derived from the volcanoes that were in eruption in that area during early Tertiary times (*Fig.* 140); not only has contact with the lava baked the adjacent chalk, turning it into a hard crystalline marble, but the capping of lava is itself responsible for the preservation of those interesting outliers of Cretaceous rocks which would otherwise have been removed by the denudation that, during Tertiary times, cleared away the Mesozoic rocks from most of the western country.

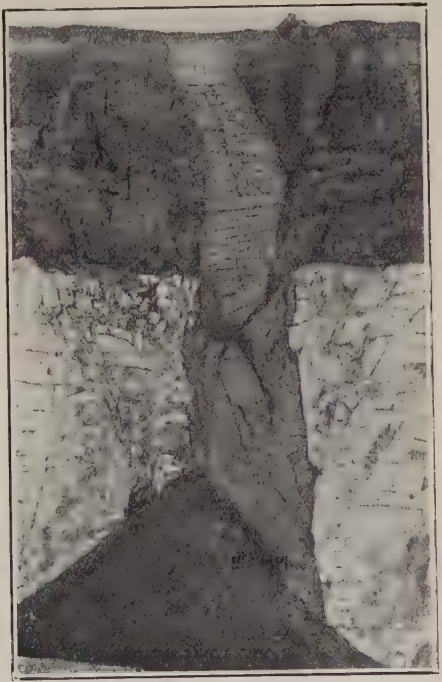

FIG. 140.—CHALK COVERED BY AND PENETRATED BY AN IGNEOUS ROCK, BASALT. Northern Ireland.

The origin of the Chalk. — The origin of the Chalk can best be considered in relation to the geographical conditions under which it accumulated.

The widespread depression, to which reference has already been made, continued, until by Upper Chalk times practically the whole of the British area was submerged; only the highest mountain regions remained as islands surrounded by a sea that extended eastwards across Europe at least as far as Russia. We have evidence, in the shallow-water type of deposit that occurs in the Irish and Scottish Cretaceous strata previously described, of the limits of the sea and of the existence of the islands, but the map (*Fig.* 141) which is based upon that of Jukes-Browne, provides an interesting example of the difficulties encountered when attempting to restore past geographical conditions.

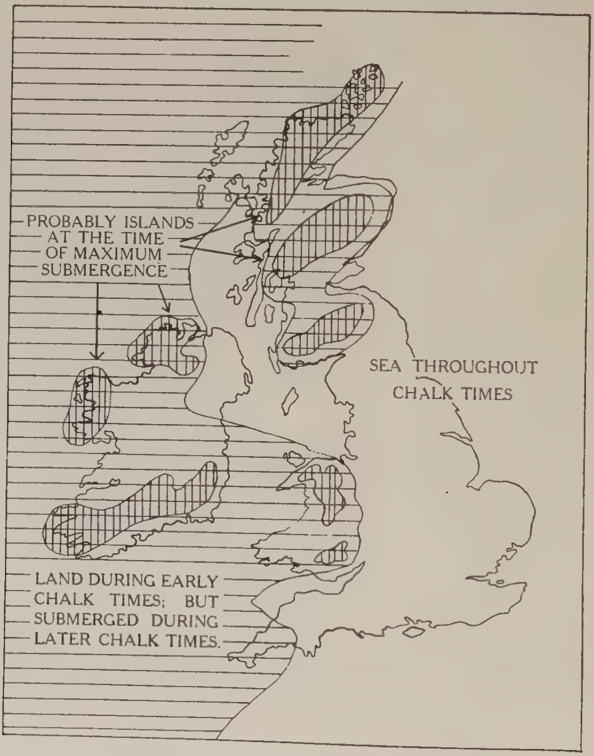
PROBABLY ISLANDS
AT THE TIME
OF MAXIMUM
SUBMERGENCE
SEA THROUGHOUT
CHALK TIMES
LAND DURING EARLY
CHALK TIMES; BUT
SUBMERGED DURING
LATER CHALK TIMES.

FIG. 141.—MAP ILLUSTRATING THE GEOGRAPHY OF CHALK TIMES.

The submergence may have been more general than the map indicates, for the insertion of the island on the site of North Wales is based upon the evidence of the *present* elevation of that tract above sea level; but although under modern conditions a widespread subsidence of several hundreds of feet would still leave the mountainous region of North Wales unsubmerged, it is by no means certain that the tract was an elevated region during Cretaceous times. Indeed, Dr. E. Greenly [5] had adduced good reasons for supposing that the Caernarvonshire mountain mass is a much denuded relic of an anticline that was raised during early Tertiary times, and that the Cretaceous sea covered the whole region. Cretaceous rocks (including chalk with flints) certainly occur on the floor of the Irish Sea, from which, even at a gentle dip (only 3°), the line of the base of the chalk, would, if projected, be carried over the summit of Snowdon.

The great subsidence of Cretaceous times is referred to by geologists as the "Cenomanian transgression," because it was due to a transgression of the sea over the land, the effects of which became most apparent during Cenomanian times (see Table on p. 249).

As the Cenomanian transgression proceeded and the expanse of sea increased, the shore lines were situated progressively farther away from our area, and the islands became not only smaller by submergence, but relatively lower by denudation, so that the amount of solid material brought down by rivers and carried into the central parts of the sea, became less in quantity and finer in grain as the Cretaceous period drew to its close; this is the explanation of the increasing purity of the chalk as it is traced from its sandy and argillaceous lower and middle portions to its white and highly calcareous upper portions. Already, by Lower Chalk times, so little land-derived debris was being brought into the sea that calcareous material constituted the greater part of the sediment that accumulated, and, with the passage of time, the amount of sandy and muddy material became less and less, until practically nothing but calcium carbonate was laid down over a wide area and for a considerable period, because, as we have seen, the Upper Chalk is very thick; it must, indeed, at one time have been even thicker, for nowhere in this country is its original top preserved, and it is impossible to determine how much was removed during the Tertiary denudations to be discussed hereafter.

Having explained the gradual development of conditions that were favourable to the accumulation of calcareous sediment, to the almost complete exclusion of land derived sediment, it now remains to consider the means by which so vast a quantity of calcium carbonate was precipitated from the sea water.

A very prevalent fossil in the chalk, especially at certain levels, is the minute foraminiferal shell, *Globigerina* (*Fig.* 142), while many other foraminifera are also present. This has given rise to a comparison between the chalk and the "*Globigerina* ooze" (a light, chalky-looking deposit, in which foraminiferal shells, especially *Globigerina*, are abundant) that is accumulating at the present time in certain parts of the ocean, especially in the Atlantic, where the depth of the water is about 2,000 fathoms or even more. The occurrence of the *Globigerina* ooze is due to the rain upon the sea floor (in parts of the ocean not reached by land-derived sediments) of shells and fragments of shells, with fragments of calcareous algæ.

It was formerly supposed, on these grounds, that the chalk was, like the *Globigerina* ooze, a *deep* water deposit, but it is now realised that although it is certainly a *clear* water deposit, the freedom from non-calcareous sediment is not so much due to the fact that the material was deposited in deep water necessarily far from land, as because the general level of the surrounding countries was such that river erosion was very feeble, and, therefore, the transport of sediment to the sea was very slight. Indeed, all the evidence suggests that the Chalk was laid down in water that was comparatively shallow. Many of the fossils, especially the molluscs, are of types that do not favour deep water, and as it is traced towards the islands or the shores, the pure chalk

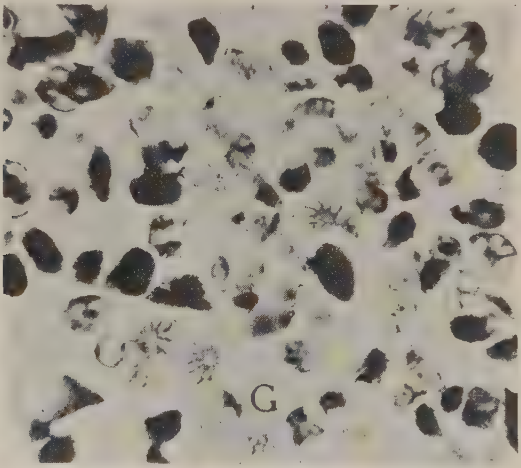

FIG. 142.—*Globigerina* (G) AND OTHER FORAMINIFERAL SHELLS, highly magnified, in ooze from the floor of the Atlantic Ocean.

passes laterally into sediments that are of shallow water origin.

Another suggestion has recently been made by W. A. Tarr, of Missouri [6]; he pointed out that if any considerable portion of the fine grained matrix of the chalk really represents minute fragments of shells, it is surprising that the larger fossils show so little signs of wear, and he believes that the fine grained material of the chalk is a chemical deposit from shallow water that was saturated with calcium carbonate. He supports his argument by reference to the minute spheroidal and ovoidal bodies which are abundant in many parts of the chalk; they are usually less than one tenth of a millimetre in diameter, and have been regarded as immature foraminifera, as simple forms of calcareous algæ, and as members of the lowly animal group known as infusoria, but Tarr compares them with oolitic grains such as those now forming in the calcareous oozes of the Bahamas and those so characteristic of the oolites and of many other limestones.

Space does not permit a fuller discussion of this interesting topic, and for further details relating to the origin of the chalk, reference should be made to the works enumerated on page 264 [7-10].

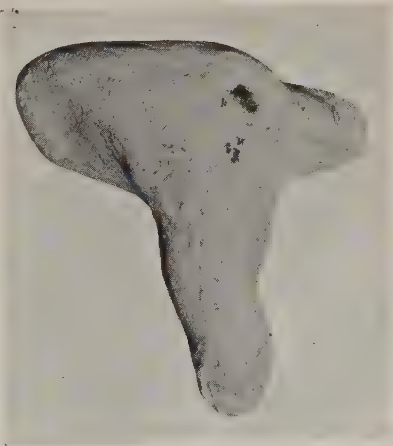

FIG. 143.—A NODULE OF FLINT FROM THE CHALK. (The specimen is about four inches long.)

Flint and chert.—One of the best known accompaniments of chalk is flint, and since a similar substance, chert, occurs in many other limestones, a brief discussion of their origin may not be out of place.

Flints are hard nodular masses of silica, indefinite in shape, and abundant in some parts of the chalk (*Figs.* 143 and 144). The interior of the flint is usually dark—often black—and the material, which varies from dull to porcelain-like in lustre, is somewhat translucent in thin chips; the outer surface is usually duller than the inside, and often consists of a definite white porous layer.

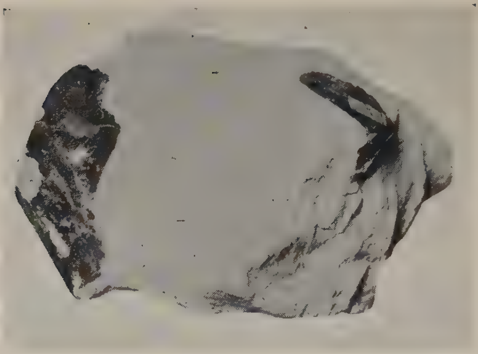

FIG. 144.—Flint nodules in chalk.
(The specimen is about four inches long.)

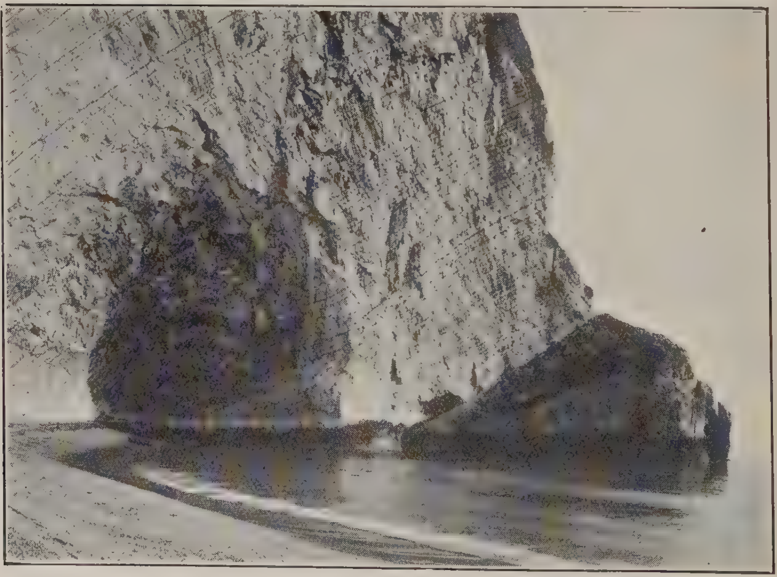

FIG. 145.—Bands of flint in a chalk cliff.

Scratchell's Bay, Isle of Wight. The inclined dark bands are layers of flint nodules that emphasise the stratification of the rock. (Reproduced by permission of the Director of the Geological Survey.)

The outer layer is composed, like the main mass of the flint, of silica, and it owes its whiteness to its porosity; it is an aggregate of minute particles separated by equally minute air spaces, so that there is an infinite number of small reflecting surfaces that scatter the light; for a similar reason snow and foam are white, whilst ice and water are transparent.

Flint may occur as thin continuous bands with irregular surfaces, but it is more frequently found as layers of irregularly shaped nodules following the direction of the bedding of the rock (*Fig.* 145); sometimes the material fills joint-fissures, indicating that it was formed after the accumulation and consolidation of the chalk.

Flint often encloses fossils, and when examined microscopically, its structure and mechanical constitution is seen to resemble that of the chalk itself, which, taken in conjunction with the evidence afforded by the form and distribution of the nodules and layers of flint, suggests that the substance is a siliceous material that has actually replaced certain parts of the chalk.

The silica appears to have been derived from the skeletal remains of animals, such as sponges and radiolaria, that were abundant in the chalk. After the death of the animals the skeletons were usually broken up, although some were preserved more or less intact (see *Fig.* 134). The silica, dissolved in the water with which the calcareous ooze was saturated, travelled through the rocks as a siliceous solution, and was subsequently redeposited in the form of bands or nodules of flint.

It has been suggested that the nodules themselves were due to the activities of siliceous sponges or some other silica-secreting animals, but while it is certainly true that flint nodules often enclose fossil sponges, and that the siliceous sponge skeleton may in some cases have determined the actual place of deposition of the silica, recent work indicates that although the silica was of organic origin, its deposition as flint was determined by chemical and physical processes. W. A. Richardson has shown that there is a much higher percentage of silica in the lower part of the Chalk in which flints are rare, than in the upper part of the Chalk in which they are common [11]. He also calculated that if the silica of the flints were diffused throughout the Upper Chalk, it would make the amount of silica in the rock itself approximately equal to that in the Lower Chalk (about 2 per cent.) and suggests that the silica, originally of organic origin, passed into solution, was diffused through the chalk, and has been concentrated at various levels according to the operation of the laws that govern the diffusion of solutions.

This phenomenon has been studied by the German chemist, Liesegang, who has shown that if a solution is diffusing through a medium containing something with which it can inter-act, it moves into the medium until the concentration of the solution becomes sufficient to form a zone of precipitate as a result of the interaction of the two. In the same way a solution may move through a suitable medium until a concentration sufficient to induce precipitation is reached; the solution then penetrates through the precipitate and travels further into the medium until the conditions are repeated and a second zone of precipitate is produced, and so on. Some such process may have taken place as the chalk-laden sea floor was uplifted after the close of the Cretaceous period and the sea water drained out of it.

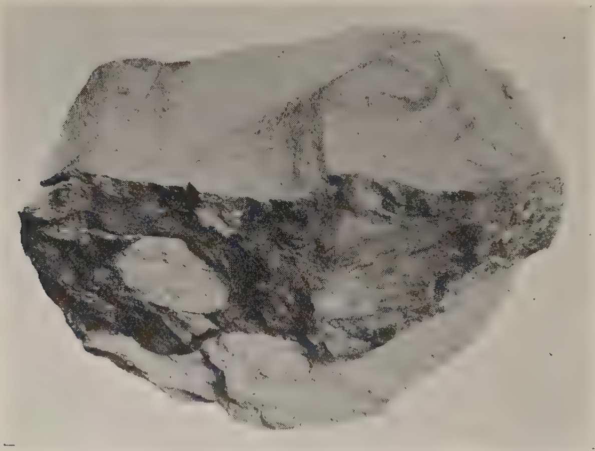

FIG. 146.—A CHERT NODULE IN A JURASSIC LIMESTONE. (Portland Beds)—specimen about seven inches long.

In Mull, where chalk is associated with deposits of greensand, the whole of the rock (which is from 10-12 feet in thickness) has been silicified, but this phenomenon is different from the silicification that results in the development of flint. It would appear that when first elevated into the condition of dry land the rock was an ordinary chalky limestone, and it developed fissures and cavities on weathering as is usually the case with calcareous rocks. At a later date the cavities were filled by wind-blown siliceous sand, and subsequently the whole was impregnated by, and the calcareous material replaced by, silica, probably at a time when desert conditions prevailed, and the evaporation of the water resulted in the development of very concentrated solutions within the pores of the rock [12, 13].

Nodules and masses of silica also occur in other limestones, as for example, those of Portland (*Fig.* 146) and Purbeck, the Lias, and the Carboniferous Limestone; but to these the name chert is given. Chert, which is similar to flint in its origin, also results, in some cases at least, from the local silicification of limestone, and the facts that it is often less translucent, and is flatter in its fracture than flint, are, no doubt, due to differences between the constitution and texture of the limestones that have been replaced.

In some localities there are thick and extensive deposits of chert, such as those associated with the Carboniferous rocks of Flintshire and Denbighshire, which cannot have resulted from the wholesale replacement of limestone by silica, and in a recent paper Mr. H. C. Sargent has suggested that such cherts were formed at the same time as the rocks among which they occur, as a result of chemical processes leading to the coagulation and precipitation of silica [13a, 13b].

Flint and chert have many uses; flint has been extensively used for building purposes and as a roadstone, and both of the substances have been used in glass making because they consist largely of silica, and in grinding mills (*Fig.* 106), because they are hard. Flints newly derived from the chalk are not good for road-making on account of their brittleness, but after some years' exposure they become tougher: this probably accounts for the esteem in which flint was formerly held as a road-making material, for, originally, the supply was derived from river beds, from dry valleys in the chalk country, or was picked from the surfaces of fields. The tower of St. Clement's Church, Hastings, is an instance of the use of dressed flints for building purposes, and other examples are to be seen throughout the Chalk districts, as, for example, at Lewes and in the Chiltern country.

In past times, flint, which emits sparks when struck with steel, was used for making fire by means of the "tinder box," and to ignite the charge of old fashioned guns; the shower of sparks produced by the contact between a rotating steel disc and a piece of flint was used in the 18th century "Steel Mill" as a source of light in gassy coal mines. Although so intimately associated with them, flint and chert are, however, not limestones, and cannot be further discussed here.

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2a. 1926—White, H. J. O., "The Geology of the Country near Lewes," *Memoirs of the Geological Survey, England.*

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9. 1914.—Drew, G. H., "On the Precipitation of $CaCO_3$ in the Sea by Marine Bacteria and on the Action of Denitrifying Bacteria in Tropical and Temperate Seas," *Carnegie Inst. of Washington*, Pub. 182, Vol. 5, pp. 7-45.

10. 1893—Hume, W. F., "The Genesis of the Chalk," *Proceedings Geologists' Association* (London), Vol. 13, pp. 211-246.

11. 1919—Richardson, W. A., "The Origin of Cretaceous Flint," *Geological Magazine* (London), Vol. 56, pp. 535-547.

12. 1925—Lee, G. W. & E. B. Bailey, "The Pre-Tertiary Geology of Mull, Loch Aline, and Oban," *Memoirs of the Geological Survey, Scotland.*

13. 1925—Bailey, E. B. & E. M. Anderson, "The Geology of Staffa, Iona, and Western Mull," *Memoirs of the Geological Survey, Scotland.*

13a. 1929—Sargent, H. C., "Further Studies in Chert," *Geological Magazine* (London), Vol. 66, pp. 399-413.

13b. 1921—Sargent, H. C., "The Lower Carboniferous Chert Formations of Derbyshire," *Geological Magazine* (London), Vol. 58, pp 265-278.

The following are among the many works in which the fossils of the Cretaceous rocks are described: each of them will be found to contain further references to the branch of the subject to which they relate:—

14. 1853-65—Sharpe, D., "Mollusca of the Chalk," *Monograph, Palæontographical Society* (London).

15. 1926—Spath, L. F., "On new Ammonites from the English Chalk," *Geological Magazine* (London), Vol. 63, pp. 77-83.
16. 1921-28—Spath, L. F., "The Ammonites of the Gault," *Monograph, Palæontographical Society* (London).
17. 1896-7—Woods, H., "The Mollusca of the Chalk Rock," Part I., *Quarterly Journal Geological Society* (London), Vol. 52, pp. 68-98; Part II., Vol. 53, pp. 377-404.
18. 1899-1913—Woods, H., "The Cretaceous Lamellibranchia of England," *Monograph, Palæontographical Society* (London).
19. 1912—Woods, H., "The Evolution of the Genus *Inoceramus* in the Cretaceous Period," *Quarterly Journal Geological Society* (London), Vol. 68, pp. 1-20.
20. 1864-82—Wright, T., "The British Fossil Echinodermata from the Cretaceous Formations: Vol. 1, Echinoidea," *Monograph, Palæontographical Society* (London).
21. 1891-1908—Sladen, W. P. & W. K. Spencer, "The British Fossil Echinodermata from the Cretaceous Formations: Vol 2, Asteroidea and Ophiuroidea," *Monograph, Palæontographical Society* (London).
22. 1916-19—Woodward, A. S., "The Fossil Fishes of the English Wealden and Purbeck Formations," *Monograph, Palæontographical Society* (London).
23. 1902-12—Woodward, A. S., "The Fossil Fishes of the English Chalk," *Monograph, Palæontographical Society* (London).

The application of fossils to the subdivision of the Chalk is dealt with in the following papers:—

24. 1899-1908—Rowe, A. W., "The Zones of the White Chalk of the English Coast," *Proceedings Geologists' Association* (London).
Kent and Sussex, Vol. 16, p. 289.
Dorset, Vol. 17, p. 1.
Additional Note on the White Chalk of the Western Cliffs of Dover, Vol. 17, p. 190.
Devon, Vol. 18, p. 1.
Yorkshire, Vol. 18, p. 193.
Isle of Wight, Vol. 20, p. 209.
25. 1930—Messent, C. J. W., "The Old Cottages and Farmhouses of Norfolk"; describes the use of chalk and flint in building.

CHAPTER XII.

LIMESTONE IN THE TERTIARY AND RECENT SYSTEMS OF ROCKS.

> "Upheaval has, as it were, raised the rough block of marble, but erosion has carved that block into the graceful statue."
>
> SIR A. GEIKIE, "*Text-book of Geology*," p. 911, 1882.

The deposition of the chalk was the last great limestone-forming episode in the geological history of this country, for the commencement, early in the Tertiary Era, of a period of violent earth-movement, caused the waters of the Chalk Sea to migrate to other areas, and the ocean was never again able to re-establish itself over the site of this country as an expanse of water sufficiently extensive and clear to permit the accumulation of a pure calcareous deposit; the small amount of limestone that does occur among the British Tertiary strata is almost entirely of freshwater origin. There was, however, a great sea on the site of, but much more extensive than the present Mediterranean Sea. An ocean had existed there almost continuously from Triassic times onwards, and during the earlier part of the Tertiary period it covered the area now occupied by the Alps, Italy, and the Caucasus, and extended into Northern Africa, and to the eastern end of the Himalayas.

Limestone was deposited in this sea, which teemed with life; some of the most interesting members of the fauna belonged to the genus *Nummulites* (*Fig.* 147), so called from its resemblance to a disc or a coin (from the Latin *nummarius*, pertaining to money). The nummulites were giants among the foraminifera, which were usually minute as in the case of *Globigerina*, for they often reached a diameter of half an inch and they were sometimes as much as four inches across.

In many places, the limestones of the early Tertiary Mediterranean Sea which attain a thickness of thousands of feet, consist largely of the shells of *Nummulites* and other foraminifera, and in places they have been converted into a compact crystalline marble-like rock, that is more like a Palæozoic limestone than one comparatively so young.

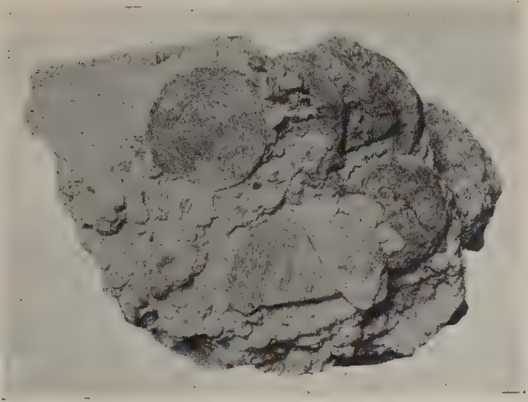

FIG. 147.—NUMMULITIC LIMESTONE.
A foraminiferal limestone of Tertiary age from Egypt. (Specimen about four inches long.)

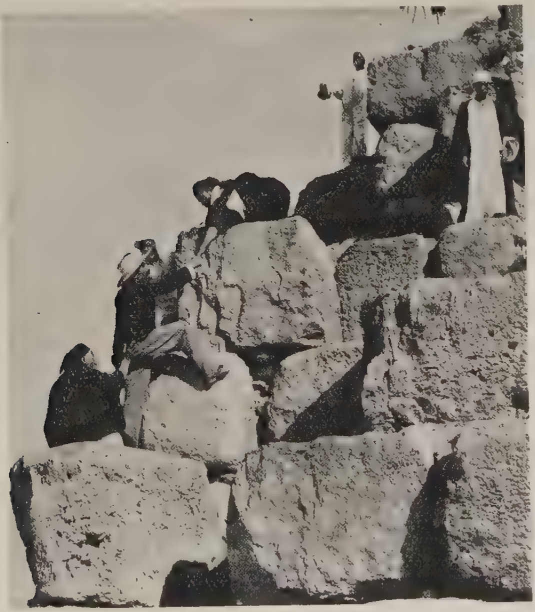

FIG. 148.—THE LIMESTONE BLOCKS OF THE GREAT PYRAMID. (*Photo J. P. Sebah*: by courtesy of the Gresham Publishing Company.)

Some varieties have been extensively used for building purposes, as for example in the construction of the Pyramids (*Fig.* 148). Here the disintegration of the rock has caused local accumulations of the disc-like nummulite shells, and an interesting belief relating to their origin is recorded by Strabo, the Greek geographer who lived towards the end of the first century, B.C.

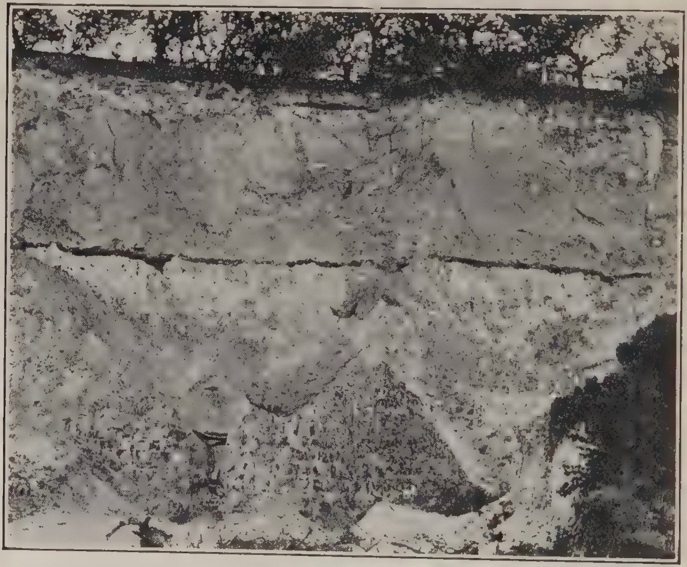

FIG. 149.—EOCENE DEPOSITS (THANET SAND) RESTING UPON CHALK:

Erith, Kent. On the top of the Chalk there is a layer of flint nodules—the residue from Chalk that has been dissolved from beneath the covering of Thanet Sand by percolating water. The flint nodules have a thin coating of the green mineral glauconite, derived from the sands. (Reproduced by permission of the Director of the Geological Survey.)

The Pyramids were, by then, ancient structures, and Strabo tells us that it was locally supposed that the round bodies were the remains of food (lentils) such as was eaten by the pyramid builders, that had with the passage of time been converted into stone. Herodotus, another Greek writer who lived in the fifth century, B.C., also referred to the fossil shells found in various parts of Egypt, and concluded that they indicated that the sea had once covered the land. This is one of the earliest observations upon geological phenomena of which we have any record.

In Europe the Eocene Nummulitic Limestone occurs around the Lake of Thun in Switzerland, and species of *Nummulites* are also present in the English Eocene strata, but not in sufficient abundance to constitute beds of limestone.

Commencement of the Tertiary Era in Britain.—In our own country the clear Chalk sea persisted long enough to permit the deposition of many hundreds of feet of limestone, after which the Cretaceous period, and with it the Mesozoic Era, came to a close when an upward movement caused the sea to retreat. The earth movements were at first slight, but they raised much of the region a little above sea level, and exposed to denudation the recently formed chalk. In consequence, there is an unconformity, often considerable, between the Cretaceous and Tertiary strata, but it is not usually very apparent because there is rarely a marked difference between the dips of the two sets of rocks (*Fig.* 149).

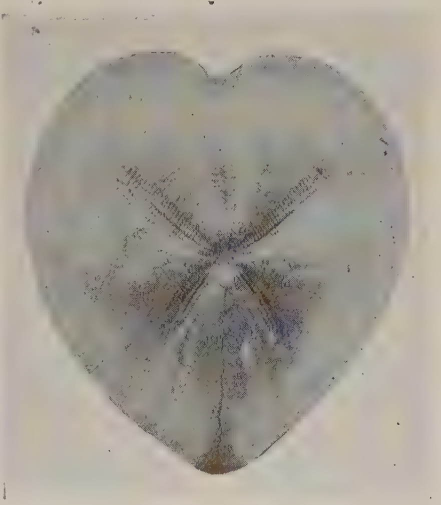

FIG. 150.—A FOSSIL SEA-URCHIN.

Micraster cor-anguinum (Leske) from the Chalk of Banstead, Surrey; natural size.

Although the Upper Chalk is so uniform over wide areas and for a considerable thickness, it has, like many other thick deposits, been divided into zones based upon the distribution of the fossils. In the Upper Chalk, for example, the echinoderm *Micraster* (*Fig.* 150) shows a gradual change in many of its characters, such as the arrangement of the plates and the pores of the five depressed areas on the upper surface of the shell, and the late Dr. A. W. Rowe showed that it is possible to recognise a level in the chalk, by considering the stage in the evolution of *Micraster* represented by the specimens of that fossil occurring in it [1]. When the fossil zones of the Chalk are studied it is found that the Tertiary rocks may rest on chalk belonging to almost any part of six of the seven zones into which the Upper Chalk is divided, and the magnitude of the unconformity then becomes apparent.

The rocks of the Tertiary Systems.—The Tertiary rocks are difficult to classify for they occur in isolated areas; certain areas that are now separate were probably at one time continuous, but owing to the folding and denudation to which they have been subjected, the intervening strata have been completely worn away.

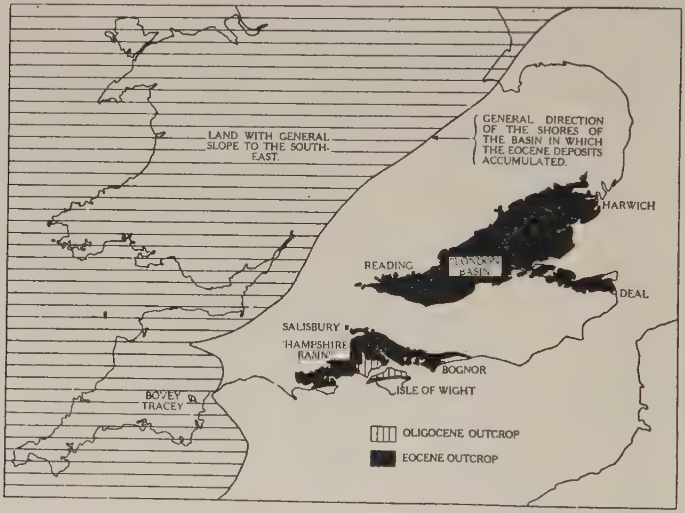
LAND WITH GENERAL SLOPE TO THE SOUTH-EAST.
GENERAL DIRECTION OF THE SHORES OF THE BASIN IN WHICH THE EOCENE DEPOSITS ACCUMULATED.
HARWICH
READING
LONDON BASIN
DEAL
SALISBURY
HAMPSHIRE BASIN
BOGNOR
ISLE OF WIGHT
BOVEY TRACEY
OLIGOCENE OUTCROP
EOCENE OUTCROP

FIG. 151.—MAP ILLUSTRATING THE GEOGRAPHY AND DEPOSITS OF EARLY TERTIARY TIME.

The area in which the early Tertiary (Eocene) rocks were deposited occupies the eastern and south-eastern portion of the region covered by the map, and the present outcrops of the Eocene and Oligocene rocks are practically confined to the districts known as the London Basin and the Hampshire Basin respectively.

With the exception of a few outlying patches, the Tertiary rocks of this country occur in two shallow depressions or basins in the surface of the Chalk, known respectively as the "London Basin" and the "Hampshire Basin"; the former coincides roughly with the lower part of the valley of the Thames, and is a triangular area with its apex near Reading, its northern limb extending to Aldeburgh in Suffolk, and its southern limb to Sandwich in Kent; the latter includes much of the county of that name, parts of the adjacent south coast counties, and the northern half of the Isle of Wight (*Fig.* 151).

So little limestone is present in the Tertiary rocks of this country that it is not necessary to discuss each of the divisions separately; all that it is necessary to say concerning the rocks and characters of the various horizons can be included in the following table which shows the classification of the System :—

DIVISIONS OF THE TERTIARY STRATA.

Pliocene: sandy and shelly deposits, often friable or incoherent, of shallow water origin, and developed principally in the coastal region of East Anglia.*

Miocene: no deposits definitely known to be of Miocene age occur in this country, but some strata with lignite (a kind of coal) at Bovey Tracey in Devonshire may belong to that epoch. Miocene deposits (sandstones and conglomerates) are extensively developed in southern Germany and Austria.

Oligocene: marls and limestones, developed only in Hampshire and the Isle of Wight; the deposits are mostly of freshwater or brackish water origin, but some beds are marine and others include terrestrial deposits.

Eocene: conglomerates, sands, sandstones, and clays, almost entirely of marine origin, developed especially in the Thames Basin and the Hampshire Basin; there are no limestones, but one of the divisions, the *London Clay*, contains layers of nodules rich in calcium carbonate (septarian concretions).

The names of the divisions refer to the relative abundance among their fossils, of species (especially of mollusca) that are still living: nearly a century ago, Sir Charles Lyell noticed (*a*) that the fossils in the higher Tertiary strata included many forms closely resembling animals now living, and (*b*) that the proportion of recent forms decreased as the strata were traced from higher to lower beds. The names used for the various subdivisions are based upon these observations—Eocene meaning the dawn of recent (life), Oligocene, a few recent, Miocene, a minority of recent, and Pliocene, a majority of recent. Lyell proposed the first and the last two, and the term Oligocene was introduced later for a division originally called Upper Eocene.

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* The strata that are newer than Pliocene—Pleistocene and recent beds —will be discussed at a later stage.

The life of the Tertiary Era.—Apart from other considerations, the existence of a great gap in the rock sequence between the present top of the Chalk and the base of the Tertiary deposits is indicated by the marked difference between the fossils of the two sets of strata. Except for certain lowly forms such as the foraminifera, it is doubtful if, of all the thousands of species of animals and plants represented by the Cretaceous fossils, any survived in this area into Tertiary times. Many Genera and even Families are, of course, common to both groups of strata, but taken as a whole the Tertiary faunas and floras bear a closer resemblance to those of to-day than do any of those which occur in the older rocks.

Among the animal groups that completely disappeared before the formation of the earliest Tertiary rocks were the ammonites and the belemnites, while the brachiopods, which had been so important until Jurassic times, are represented only by a few Tertiary species, the individuals of which were never abundant. Bivalved and univalved molluscan shells (lamellibranchs and gastropods), however, had become very numerous, especially the latter, which have steadily increased in importance until at the present day they are, perhaps, the dominant invertebrate marine animals. The scarcity of limestones among the British Tertiary rocks is, therefore, in no way due to a lack of organisms capable of secreting calcium carbonate; it is to be attributed to the fact that the earth-movements of the time, shortly to be discussed, were such that a clear sediment-free sea, which is essential to limestone-formation, was never able to develop in the region.

The reptiles, so important during Jurassic times, reached their culmination in the Cretaceous period; they must have declined with startling rapidity, and most of the groups characteristic of the Age of Reptiles died out before the lowest Tertiary strata accumulated, because their fossil remains are scanty in the rocks of that age, and such as do occur indicate a reptile fauna not much unlike that of the present day. The fish fauna of the Tertiary Era is also much like that of to-day, but the most interesting feature connected with its vertebrate fossils, is the evidence of the rise of the mammals. This great animal group, represented by a few lowly forms during the Age of Reptiles, increased in size, in variety of form, and in diversity of habit as Tertiary times progressed, and the mammals, of which man is the highest member, are now the dominant vertebrate animals.

The record of plant life during Tertiary times is similar to that of the animals—the giant clubmosses, ferns, and cycads of the earlier periods had declined, and flowering plants had become important, so that even in the Eocene period the vegetation was beginning to assume its modern aspect.

Geographical changes during the Tertiary Era.—The earlier Eocene rocks are essentially marine, but they are of shallow water origin, and must have been laid down in the neighbourhood of large rivers flowing from the south and east into a basin that occupied the southern part of the country; land lay to the north and west, because in Mull and Antrim there are land-deposits (soils and plant remains), preserved beneath the lavas (basalt) and ashes ejected from volcanoes active in that region early in Tertiary times [2]. Most of the volcanic material has been lost by denudation or by subsidence beneath the sea, but, as we have seen, when discussing the Cretaceous and Jurassic limestones, small portions still remain on the north-eastern coast of Ireland, the west coast of Scotland, and many of the islands between.

No true limestones occur among the Eocene strata, but some nodules rich in calcium carbonate occur in the London Clay, and will be referred to subsequently.

The earth movements that brought the accumulation of the Cretaceous rocks to a close in the European area were still in progress in early Tertiary times, and were, indeed, increasing in intensity, for the later Eocene rocks indicate a still further shallowing of the water basins, and the deposits are in part estuarine; before long, parts of the Eocene sea-floor were raised above sea level, so that both estuarine and freshwater deposits are important among the Oligocene strata, which, in this country, occur only in the Hampshire basin. The fossils include not only freshwater shells, but land shells, plant-remains and insects, all of which indicate the terrestrial origin of the strata. Some interesting freshwater limestones accumulated at this time, but, as with the calcareous nodules of the Eocene clays, it will be more convenient to defer their discussion until the Tertiary geographical changes have been dealt with.

The upward movement continued during and after the deposition of the Oligocene rocks, and eventually most of the British area was raised until it became dry land, a condition in which it remained for a very long time—indeed, parts have probably never since been submerged.

The result of the uplift and denudation is that, with the possible exception (in Devonshire) already mentioned, the Miocene

Period is not represented by strata in this country; indeed, the inconsiderable thickness (only about 3,000 feet) of the Tertiary rocks is no indication of the length of Tertiary times, because during the periods of denudation, which must have been very long, not only were no new strata laid down, but much material already deposited was worn away.

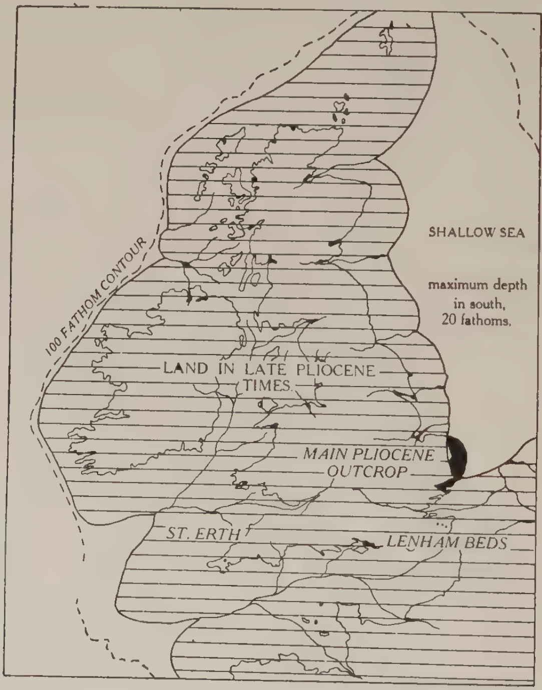
100 FATHOM CONTOUR
SHALLOW SEA
maximum depth in south, 20 fathoms.
LAND IN LATE PLIOCENE TIMES.
MAIN PLIOCENE OUTCROP
ST. ERTH
LENHAM BEDS

FIG. 152.—MAP ILLUSTRATING THE GEOGRAPHY OF LATE PLIOCENE TIMES AND THE PRESENT DISTRIBUTION OF PLIOCENE DEPOSITS.

The main Pliocene outcrop is the small blackened area in East Anglia; small patches of Pliocene strata also occur in Kent (the Lenham Beds) and at St. Erth, in Cornwall.

The earth movements which affected the rocks of this country were part of the great world-wide series of upheavals that determined the form and essential structures of the present continents. The movements were intense and widespread, because even the earlier formed Tertiary rocks were among those raised into the folded mountain masses that stretch across the Old World as the Pyrenees, the Alps, the Carpathians, and the Himalayas, and that occur in the west of America as the Rockies and the Andes: in places Eocene deposits are now as much as 16,000 feet above sea level.

Although the Miocene deposits are absent from this country, there are some thick and important Miocene limestones in Europe, and the Miocene conglomerates (*Nagelfluh*), which occur on the north side of the Swiss Alps, often consist largely of pebbles of limestone derived from Mesozoic rocks that were undergoing denudation during Tertiary times.

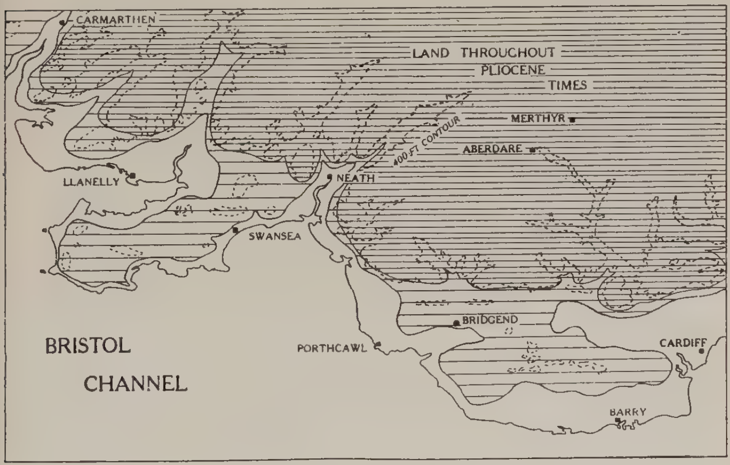

FIG. 153.—MAP ILLUSTRATING THE COASTLINE OF SOUTH WALES DURING PART OF PLIOCENE TIMES.

The area indicated by close parallel lines probably remained as a land region throughout Pliocene times, but the coastal tracts were submerged during part of the period. When the general level of the land was about 400 feet lower than at present the coast was a little further north, but as the subsidence of Pliocene times progressed, the tract indicated by more widely spaced parallel lines was in all probability submerged also.

Towards the end of the Miocene period subsidence once again commenced; it affected south-eastern England and the adjacent parts of the continent, and the return of the sea resulted in still further denudation of the Tertiary and Cretaceous rocks, and produced a more or less level surface on which the Pliocene deposits accumulated. It is improbable that the submergence affected more than the low-lying and coastal regions, because no marine Pliocene deposits are found in the midland and north-west country, and, except for small patches in Cornwall, Kent, and Surrey, they are confined to East Anglia (see *Fig.* 152): in some areas (Cornwall, Devon, South Glamorgan, Pembrokeshire and Anglesey), there is positive evidence that the *coastal* regions only were submerged and levelled off by the sea in Pliocene times—the highland regions further from the sea (the hills of the South Wales Coalfield, for example) remaining as dry land areas (*Figs.* 153 and 154); see Additional Note, page 451.

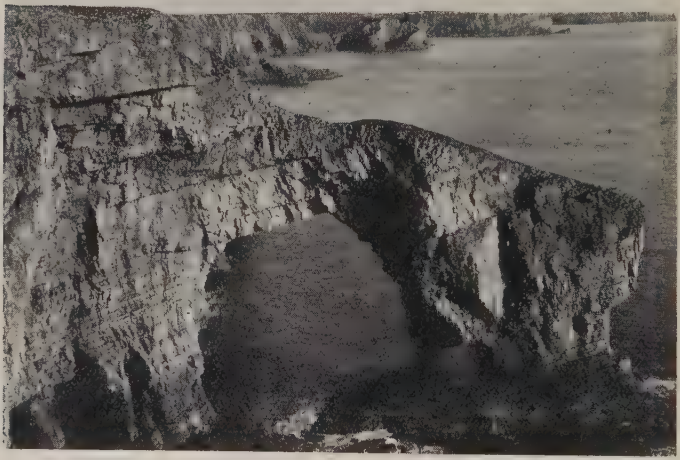

FIG. 154.—THE "GREEN BRIDGE OF WALES."

Cliffs of Carboniferous Limestone west of Bosherston, Pembrokeshire, showing that planes of bedding and jointing promote the destruction of the cliff. The even land-surface is part of the area levelled by wave action in Pliocene times. (Reproduced by permission of the Controller of H.M. Stationery Office and the Director of the Geological Survey.)

The Pliocene strata are so-called because of the abundance of shells of modern types that are included among their fossils, but they are also known as "Crag," from the Celtic word *cregga*, meaning a shell, because shells constitute a large part of some of the beds; *Fig.* 155. Various subdivisions of the Pliocene are recognised in East Anglia; the principal are, in descending order:—

PLIOCENE SERIES.

Cromer Forest Bed Group — sand, clay, and gravel, of estuarine and freshwater origin; named from Cromer, where the beds are well displayed.

Norwich Crag—light coloured fossiliferous sands, with many shells and the bones of large mammals, including extinct elephants.

Red Crag—very fossiliferous sands, the prevailing tint of which is red owing to the presence of iron peroxide.

Coralline Crag—a yellow sandy rock, well exposed in Suffolk; contains many shells and abundant remains of polyzoa; the latter were formerly thought to be related to the corals, hence the name given to the beds.

The shelly deposits of the Crag accumulated in shallow water —some of them as shell banks, raised by the combined action of sea currents from the south-west and of strong winds from the east, and many of the beds might be regarded as limestones but for the fact that so little consolidation of the material has taken place. In places, the shelly beds have been dug for the purpose of providing calcareous material for agricultural purposes—for "marling" as it is called.

There are other "Crags" (such as the *Chillesford Crag* and the *Weybourne Crag*) but they are of limited distribution, and the various divisions of the Pliocene strata do not all occur one above another like the various zones of the Chalk or of the Carboniferous Limestone; they succeed one another laterally rather than vertically, the oldest occurring only in the south. It would appear that the main part of the "Crag" accumulated as beach deposits, in a sea, the shore of which was moving slowly northwards, so that, in general, newer beds are encountered as the Pliocene outcrop is traced from south to north.

The mollusca represented by the fossil shells in the Coralline Crag are, on the whole, similar to those now living in the Mediterranean sea, but as the newer deposits come in further north, the proportion of shells of southern types is found to diminish, and shells belonging to or allied to species that now inhabit the cooler waters of the north become increasingly numerous, until, in the latest formed Pliocene beds, the fauna is essentially like that of the arctic seas; in addition, the plant remains preserved in the

Cromer Forest Bed include the arctic willow and a dwarf birch, and are also indicative of a cold climate. This change in the character of the fossils was due to the approach of the period of intense cold known as the Glacial Period or the Great Ice Age, which will be discussed more fully in connection with the Pleistocene epoch.

It is necessary at this point to break the narrative of the events of the Tertiary Era in order to refer to the interesting, although at present unimportant calcareous beds and limestones that occur among the Oligocene and Eocene rocks.

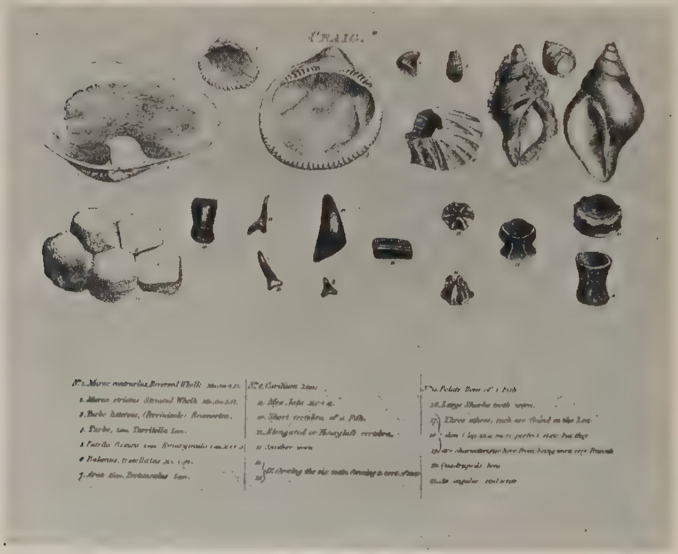

FIG. 155.—FOSSILS FROM THE (PLIOCENE) CRAG.

This is a photograph of one of the Plates in "*Strata Identified by Organised Fossils*," published by William Smith, in 1816. It affords an illustration of the principles he laid down, namely, that each of the various rock formations has its own characteristic fossils.

Limestones in the Oligocene Series. — For the same reason that Miocene rocks are absent from this country, part only of the Oligocene Series, as developed on the continent, is present here. The beds are confined to the Hampshire Basin, where they include the following subdivisions :—

Oligocene Series.

Hamstead Beds—mainly freshwater marls and clays, with a thin clay containing marine shells at the top.

Bembridge Marls—mostly freshwater marls and clays.

Bembridge Limestone—freshwater, shelly *limestone*, pale in colour.

Osborne Beds—red and green clays and grits, with some thin impersistent freshwater *limestones*.

Headon Beds—clays, marls and sands, with occasional beds of *Limestone*: the middle part of the division is marine, but the bulk is of freshwater or brackish water origin.

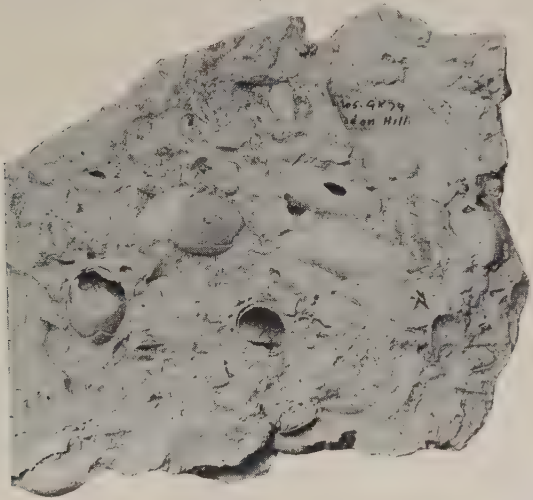

FIG. 156.—Fresh-water limestone from the (Oligocene) Headon Beds of the Isle of Wight.

The rock is a creamy limestone crowded with the shells of the fresh-water snail *Limnæa;* slightly reduced in size.

The divisions cannot readily be distinguished, for the rocks are variable laterally and they graduate one into another vertically: the most persistent is the Bembridge Limestone.

The *Bembridge Limestone* which varies from twelve to twenty-five feet in thickness, includes a number of layers varying in composition and texture: some varieties are hard and shelly, others are soft and tufaceous, and white or pale cream are the prevailing colours. The rock is entirely of freshwater origin, and the shells are principally those of freshwater snails such as *Limnæa*, *Planorbis*, and *Viviparus*, not unlike many of the forms living to-day in streams and ponds; *Figs.* 11 and 156.

In times past, some parts of the limestone have been quarried for building stone, principally at Binstead, near Ryde in the Isle of Wight [3, 4].

The rock was used, among other places, in a number of Sussex churches and in Winchester Cathedral, and also for constructing sea-walls on the north coast of the Isle of Wight, but except for repairs it is now seldom worked. At Brading the Bembridge Limestone has been excavated for cement-making, and after a long period of disuse, the works were re-opened a few years ago; near Tapnell it is quarried for roadstone (tar-macadam).

Algæ, and certain kinds of water plants that construct external skeletons of calcium carbonate, played an important part in precipitating the material of the limestone. Among the lime-secreting plants was *Chara* (one of the stone-worts, *Fig.* 157), which invested itself with a thin deposit of calcium carbonate, and the small globular and often beautifully ornamented seed-vessels of which are abundant in many parts of the Oligocene strata [5]. Locally, some of the beds are more like calcareous tufa or travertine, and the material may have been deposited as a result of the evaporation of water highly charged with calcium carbonate. The limestones in the Headon Beds are, in general, similar to the Bembridge Limestone.

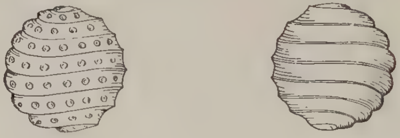

FIG. 157.—SEED VESSELS OF *Chara*, A LIME-SECRETING FRESH-WATER PLANT.

These little globular bodies, variously ornamented, and usually smaller than a pin's head, are abundant in certain of the Oligocene fresh-water limestones.

The presence of freshwater limestones in the Oligocene series suggests that the clear waters of the lakes and ponds were at times very "hard," owing to the presence of much dissolved calcareous material; this was, no doubt, due to the fact that chalk was being extensively denuded. In some respects they resemble certain modern freshwater limestones (with the shells of *Limnæa* and *Planorbis*) which occur in hollows on the surface of limestones in the Dinaric Alps (on the north-western side of the Adriatic Basin) and occupy the sites of lakes that have now drained away. In some parts of Ireland similar calcareous deposits or shell marls (now covered with peat) rest on the Carboniferous Limestone of the lowlands.

Calcareous nodules (septarian concretions) in the London Clay.—At certain horizons in the London Clay there are layers of nodular concretions sufficiently rich in calcium carbonate to be compared with argillaceous limestones. Formerly, in some districts where transport was difficult, they were the only hard stones available, and they were used for building purposes. The proportions of their argillaceous and calcareous constituents are such that when suitably treated the nodules yield cement, and even before the days of Portland Cement they were gathered on the sea shore near Harwich, in the Isle of Sheppey, and on other parts of the south-east coast, and used for cement making. The nodules were broken, ground, and heated to the point at which fusion commenced, producing clinkers which were finely ground, just as in the manufacture of Portland Cement. The resulting material, brownish in colour, was formerly called *Parker's Cement,* after James Parker who first made it and took out a patent in 1796, but it is now known as *Roman Cement.* The nodules are still gathered for cement making, but the industry is of minor importance compared with the manufacture of Portland Cement. Nowadays, the ground raw material is only raised to a moderate red heat, it having been found unnecessary to use the high temperatures of the original process. Roman Cement sets rapidly, even under water, and is, therefore, an hydraulic cement : it is, however, more variable in composition than Portland Cement, and is inferior to that material in hardness and strength [6, 7]. Since they are produced by simply heating ground rock, Roman Cement and similar materials made on the Continent and in America are called Natural Cement, but they should not be classed with Portland Cement; indeed in Germany it is an offence to sell " Natural Cement " as " Portland Cement."

The nodules—and this applies also to similar concretionary masses that occur in other clays as well as the London Clay—are usually more or less bun-shaped, the bottom being flat and the upper surface convex. They have an internal arrangement of cracks forming the boundaries of polygonal masses of stone that were at one time supposed to be seven sided, hence the name *septaria*. The cracks may be open, but in the London Clay nodules they are usually filled with the mineral calcite: their arrangement is illustrated in *Fig.* 158 and polished slices of London Clay septaria were, a few decades ago, used for the tops of small ornamental tables, in which the calcite veins, usually yellowish in colour, contrasted with the darker (brownish) matrix.

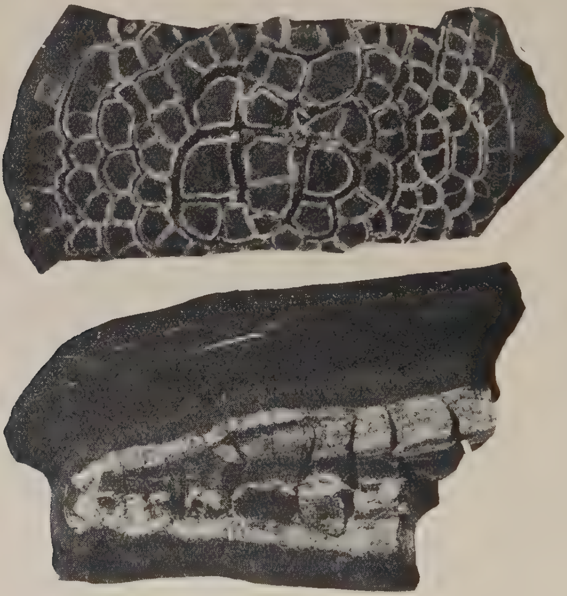

FIG. 158.—Septarian concretions.

The lower photograph of a concretion broken vertically shows the vertical distribution of the cracks, while the upper photograph of a concretion broken horizontally shows their rudely concentric arrangement. In the septarian nodules of the London Clay, the cracks are usually filled with yellowish calcite; photographs about one-fourth natural diameter.

The cracks owe their origin to shrinkage of the nodules [8, 9]. Calcium carbonate was present in the original mud—derived no doubt from the solution of shells, for the London Clay is not now on the whole very fossiliferous—and the gradual segregation of the calcareous matter, often around a fossil or some other nucleus, gave rise to patches of clay locally rich in calcium carbonate. As time went on, the outer layer of the calcareous mass became hard owing to the crystallisation of the calcium carbonate, but crystallisation is accompanied by a decrease in volume, so that when the material inside the hardened crust also crystallised, it was not sufficient to occupy all the available space, and internal cracks were developed; near the centre, the cracks arranged themselves in a polygonal fashion, while near the edge they are more or less concentric. The minerals that line the cracks in septarian concretions (in the case of those in the London Clay it was usually calcite) were deposited by the action of percolating water after the cracks were formed—it was not the case that crystallising minerals forced the fragments of the matrix apart.

The Post-Pliocene epochs and strata. — The time that has elapsed since the close of the Pliocene is divided into two epochs:—

Post-Pliocene Epochs.

Holocene—The Recent epoch: historic and later pre-historic times; the Holocene deposits are sporadic in distribution, irregular in shape and thickness, and very varied in constitution; they include the alluvial deposits in the valleys and estuaries of rivers, also peat, and tufa.

Pleistocene—The Great Ice Age: a period during which much of Europe and North America was ice-bound. The deposits include the glacial "drifts" and "boulder clays," and the Terrace Gravels of many rivers.

By some writers, the Holocene and Pleistocene epochs are together regarded as representing a fourth Era—the Quaternary (comparable with the Palæozoic, the Mesozoic and the Cainozoic of the Table on page 57); this is principally because it is the "Age of Man," but the deposits are so thin and scattered in this part of the world, and the time they represent so short compared with the very long period that must have elapsed while the Palæozoic or the Mesozoic rocks were accumulating, that it seems better to consider them merely as the most recent sub-divisions of the Tertiary Era.

The formation of calcareous deposits is, of course, a process that has gone on continuously in some place or other almost since the commencement of geological time; but, as we have seen, the sea is the great theatre of limestone formation, for freshwater limestones are comparatively rare, and limestones formed on land are even more rare. Post-pliocene time was, in this part of the world, a period of denudation rather than of marine sedimentation, so that calcareous rocks are not an important feature in Holocene and Pleistocene deposits; such as do occur are, however, interesting, but before describing them it will be convenient to complete very briefly the narrative of earth history which has been the basis of the present discussion of limestone.

The coming of the "Ice Age."—Towards the close of Pliocene times a widespread elevation resulted in the area that is now the British Isles becoming dry land once more; it was then a large mass continuous with the continent of Europe, and its western coast coincided approximately in direction with the present 100 fathom submarine contour line (see *Fig.* 152). The combined effects of a slow downward movement and of the destructive action of the waves upon the coast allowed the sea to encroach upon the western margin of the land mass, and it eventually entered (or "drowned," as it is termed) parts of some of the western river valleys, giving rise to the Bristol Channel, St. George's Channel, the Irish Sea, and the smaller inlets by which their coasts are interrupted; *Figs.* 159-160 [10].

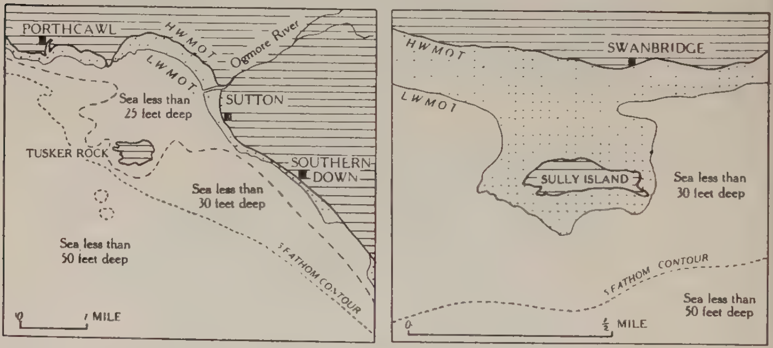
PORTHCAWL
H W M O T
Ogmore River
L W M O T
Sea less than 25 feet deep
SUTTON
TUSKER ROCK
SOUTHERN DOWN
Sea less than 30 feet deep
Sea less than 50 feet deep
5 FATHOM CONTOUR
0
1 MILE
H W M O T
SWANBRIDGE
L W M O T
SULLY ISLAND
Sea less than 30 feet deep
5 FATHOM CONTOUR
Sea less than 50 feet deep
0
½ MILE

FIG. 159.—MAPS OF PARTS OF THE GLAMORGAN COAST ILLUSTRATING COASTAL LOSSES IN HISTORIC TIMES.

Sully Island, which is only isolated at high tide, illustrates, on a small scale, the relation, at a former period, between the Tusker Rock and the mainland. The Tusker Rock has been isolated in geologically recent times, and the sea between it and the mainland is nowhere more than 25 feet deep [10].

A depression in the east had resulted in the formation of the North Sea before England was finally separated from France, or Ireland from Great Britain, but as the Pliocene epoch drew to a close the southern part of that sea became choked with deposits, and constituted a low-lying district with many shallow lakes and sinuous water-courses, not unlike the present Norfolk Broads, but, of course, much more extensive. The Rhine, as well as the neighbouring rivers that flowed across Europe from the south, continued its course across this plain, and entered the sea considerably farther north than it does to-day. A narrow winding strip of river-formed deposit (the outcrop of the Chillesford Crag) that can be traced among the Pliocene rocks of Norfolk, almost certainly represents the course taken by one of the many mouths of this ancient Greater Rhine.

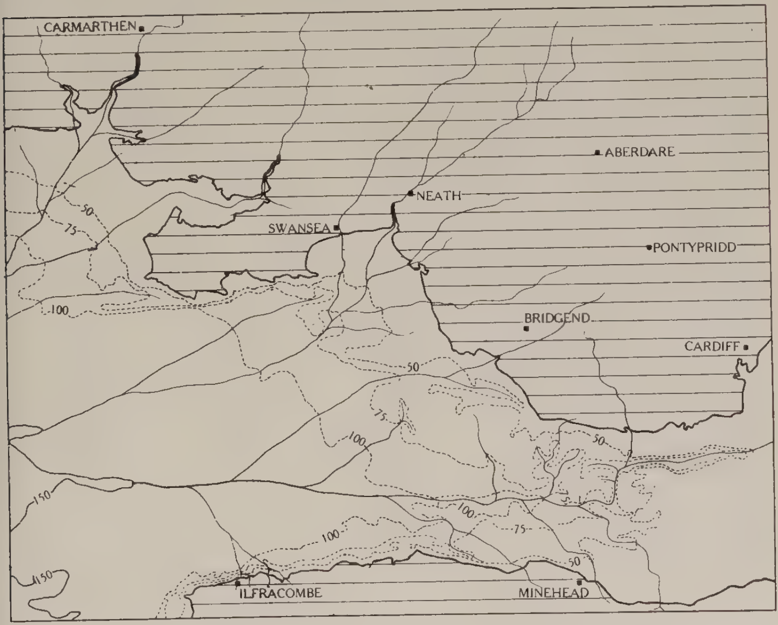

FIG. 160.—Map of the Bristol Channel with Submarine Contours.

The irregularities in the submarine contours correspond with the continuations of the river valleys at a time when the land stood at a higher level. The position of the present coast has been determined by the advance of the sea in geologically recent times.

We have already seen that one effect of the subsidence that finally separated this country from the Continent was to allow the water from the arctic seas to penetrate regions where, formerly, warmer conditions had prevailed, and the coming of the cold was an indication that profound climatic changes were impending, for, soon afterwards, a considerable part of the northern hemisphere was in the throes of an Ice Age. The average temperature was appreciably lower than at present; snow remained permanently on the mountains, glaciers filled the valleys, and northern regions like Scandinavia were as ice-bound as Greenland is to-day.

Although the deposits of the Ice Age rest with strong unconformity upon rocks of all ages, from Pre-Cambrian to late Tertiary, the passage to it from the preceding epoch was, like that between other divisions into which geological time has been divided for convenience of description, gradual. As the days grew colder, the summers shorter, and the winters longer, the animals from the cold regions wandered south in winter, but during the summer the warmth-loving animals returned for a time to their old northern haunts, until eventually the cold became sufficiently continuous and intense to keep them away altogether, and in consequence, when we study the fossil evidence of the land-animals that lived just before and during the Ice Age, we find at first the bones of northern animals, like the reindeer, mingled with those of southern forms, but the latter disappeared altogether as the glacial conditions became more firmly established.

Authorities are not agreed as to whether or not there were a number of glacial episodes separated by warmer inter-glacial periods—as evidence in parts of Europe seems to suggest—but a discussion of that problem is outside the scope of the present work [10a]. It will be sufficient to say that, in this country, it is highly probable that when glacial conditions had prevailed for a time, climatic conditions became milder, after which a cold period of even greater severity ensued, but in discussing the effects of glaciation we will speak in general terms of the period as a whole. The evidence for a warmer interglacial episode lies in the fossils (mostly plants and mammals) present in sands and gravels associated with the deposits of glacial origin.

In speaking of the "Glacial Period" it is necessary to bear in mind that the expression has not yet a definite time value like "Ordovician" or "Eocene," because although as far as this country is concerned the "Ice Age" is an episode of the remote past, and snow and ice are associated only with the winter months, the same cannot be said of the whole of Europe. In the south, snow only remains permanently on the highest mountains such as those in Switzerland, but as one goes north, the lower limit of permanent snow and ice comes steadily nearer to sea level, until in the arctic regions frozen conditions prevail even in the sea itself.

The Glacial Period or the "Ice Age."—To users of limestone the only matters of interest in connection with the Glacial Period are that in some districts it saw the removal of the superficial layer of decomposed rock-debris that had developed as a result of the long exposure to the atmospheric agents of weathering during the Tertiary Era, thus bringing comparatively fresh rock near to the surface, while in other places it saw the distribution of stony clay or gravel in irregular patches, variable in extent and thickness, thus concealing many of the earlier formed rocks beneath material that constitutes the useless and often inconvenient "overburden" of the quarryman.

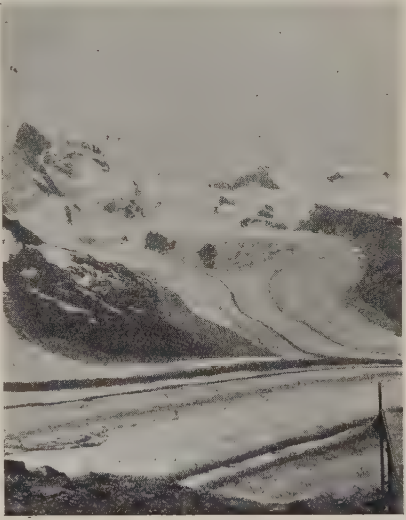

FIG. 161.—A GLACIER AND ITS MORAINE.

The Gorner glacier with Monte Rosa, Switzerland; the moraines of rock debris appear as black ribbon-like strips on either side of the glacier. (*Photo W.E.H.*)

A brief account of the manner in which these processes were carried out will be sufficient for present purposes. As, during the progress of the Glacial Period, the cold increased, snow that fell on the mountains in winter remained unmelted during the summer, building up snow-caps that steadily increased in thickness until the pressure brought the deeper layers into the condition of compact ice, and caused that ice to move, as rivers of ice, or glaciers, slowly down the valleys (*Fig.* 161). The snow-fields centred upon the mountainous masses of Great Britain and Ireland gradually increased in size, until eventually, except for the southern parts of Ireland and England, our islands were ice-bound. The evidence of the work of the ice in this country has been interpreted by comparison with its present behaviour in mountain regions, like the Alps, where it still persists. There, it is found that the constant addition of fresh snow in the higher regions results in the flowage of the lower layers and the slow passage of tongues of ice (glaciers) down the valleys, until a level is reached at which the average temperature is such that the ice melts as rapidly as it advances, and, so long as climatic conditions are constant, the end of the glacier remains stationary with a stream of muddy water flowing from it. More than one important European river originates in this way—the Rhone affords one of the best known instances.

Fragments of rock dislodged (usually owing to the action of frost) from the valley sides, roll down and gather upon the surface of the glacier, and as the ice moves, they are slowly carried along (see *Fig.* 161). At some places there may be rock ledges that in the case of an ordinary river would have given rise to waterfalls; here the ice is found to crack and descend in huge masses as ice-falls. Lower down the valleys, pressure from behind causes the cracks to close and the glacier again appears as an unbroken mass. The burden of stones will, however, to a large extent, have disappeared, for they tend to fall down the cracks produced as the ice accommodates itself to its uneven bed, and they continue their journey either at the bottom of the glacier or embedded in its mass. At the same time, the soil and any loose fragments of rock that may be on the surface over which the glacier moves are also caught up in its lower layers, and, together with the material that has fallen in from above, they cause the glacier to act after the fashion of a rasp—rubbing, polishing, and scratching the rocks over which it moves, and carrying the debris—large stones, small stones, and powdered rock, indiscriminately mixed—along with it.

Should the climate become warmer, the lower end of the glacier will retreat up the valley, and, in time, the ice of the snow-field itself may entirely disappear. As it melts, its burden of solid material is dropped, forming a jumbled mass of stones of all kinds and of all sizes, embedded in a sandy clay, that is really a kind of rock-flour produced by the grinding together of the stones, rather than a true clay, which, as we have previously seen, results from the decomposition of certain rock-forming minerals.

The result is that when the ice has disappeared from a region it once occupied, we find widespread but irregular deposits of

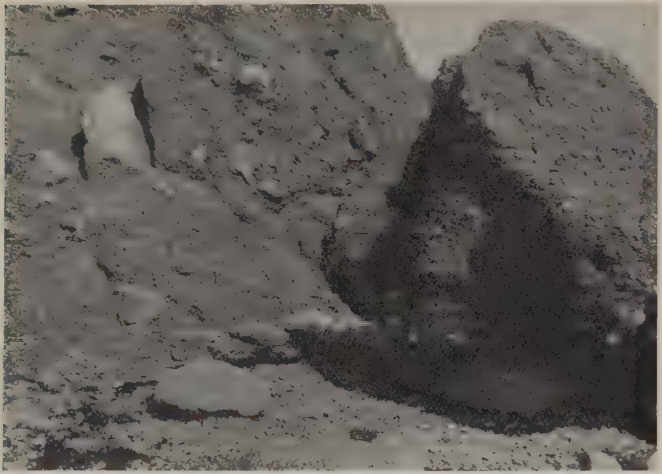

FIG. 162.—GLACIAL DEPOSITS AT CRICCIETH, NORTH WALES.

The material consists of clay containing stones and boulders of all sizes, many of them exhibiting the characteristic scratches or "striæ," as on the boulder illustrated in Fig. 164.

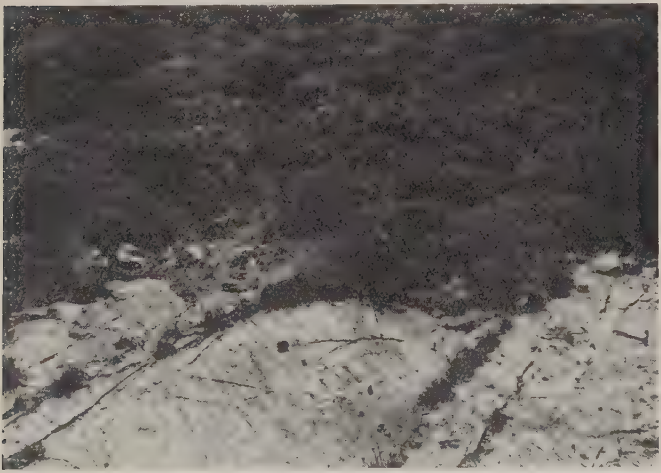

FIG. 163.—A GLACIATED "PAVEMENT."

A rock surface near Ystradfellte, Brecknockshire, smoothed by glacial action, and preserving the scratches produced as stones embedded in the floor of the moving ice passed over it.

"boulder clay," as it is appropriately called, or of gravel, with fragments of rock that may have been picked up at any spot over which the ice passed (*Fig.* 162). It is because the place of origin of such transported rock-fragments can often be determined, that it is possible to indicate the direction in which the ice moved across the country; other evidence of the movement of the ice is found in the direction of the scratches and furrows that were produced on exposed rock surfaces and have not been obliterated by subsequent weathering (*Fig.* 163). Many of the boulders and pebbles will have been polished and scratched as they were dragged along at the bottom of the ice-flow, and one of the surest indications of the glacial origin of a deposit is the presence in it of stones with surfaces that have been smoothed, often to the extent of polishing, and yet are profusely scratched (*Fig.* 164).

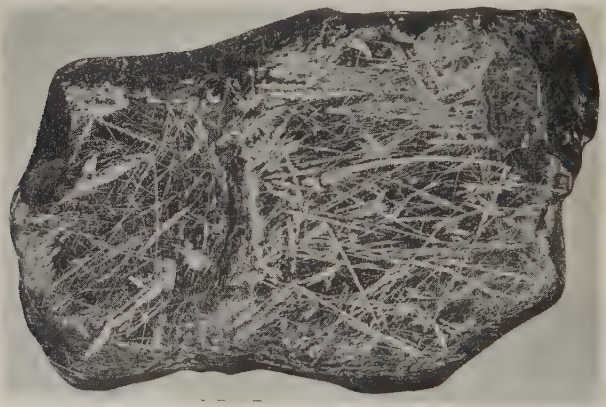

FIG. 164.—A GLACIATED BOULDER.

A small boulder about 10 inches long, of Carboniferous Limestone, from a glacial deposit, exhibiting in a remarkable degree the scratches characteristic of ice-transported stones.

The ice that once held sway in this country has left its traces in valleys that have been scoured and deepened, in rock-surfaces polished to glassy smoothness and furrowed with parallel scratches, and in accumulations of gravel, sand, and clay, such as those we have described, filling hollows that formerly existed, forming mound-like masses and ridges, and generally obscuring the "*solid*" rocks by a mantle of "*drift*," as, collectively, the glacial deposits are called.

Where the " drift " was deposited merely as a result of the melting of the ice it consists of stones of all kinds and sizes indiscriminately mixed (*boulder clay*), but in many cases the material was more or less effectively sorted by the action of the water that resulted from the melting of the ice, and thus gave rise to separate deposits of gravel, of sand, or of clay. Whatever its nature, the " drift " is very variable in character on account of the wide range of material from which it was derived, and in thickness on account of the irregularity of the floor upon which it was laid.

In cases where the glacial material has been derived largely from a limestone region, the " drift " deposits may themselves be highly calcareous. This is the case, for example, with the " Chalky Boulder Clay " of East Anglia and Lincolnshire, the nature and distribution of which are of some importance to agriculturists. The deposit provides interesting evidence of the movement of the ice, because it is found that the chalk of the pebbles present in the boulder clay of East Anglia is not like the local Chalk; it is harder and more like that found farther north in Lincolnshire and Yorkshire.

" Drift Maps."—It is important that the existence of the drift should be borne in mind by those who may have occasion to use geological maps, for it is obvious that where there is a covering of glacial material the soil bears no direct relation to the underlying rocks that enter into the geological structure of the district, from which it follows that a map intended to portray essential geological features does not of necessity indicate the nature of the material that occurs at the *surface*. At the present time it is the custom of the Geological Survey to prepare, where necessary, two maps—one showing the distribution of the glacial and other superficial deposits, and another showing the region as it would appear if all such deposits were stripped away. The former is called a *" drift "* map, and the latter a *" solid "* map, and the relation between them is illustrated diagrammatically in *Fig.* 165.

To agriculturists and those concerned with the soil, or to quarrymen who may need to know something of the overburden they may be likely to encounter, a " drift " map is essential when dealing with a district where glacial conditions once prevailed, but to those concerned with the penetration or exploitation of the more deeply seated rocks, the " solid " map usually conveys more information. The preparation and history of geological maps is discussed in a recent publication of the National Museum of Wales

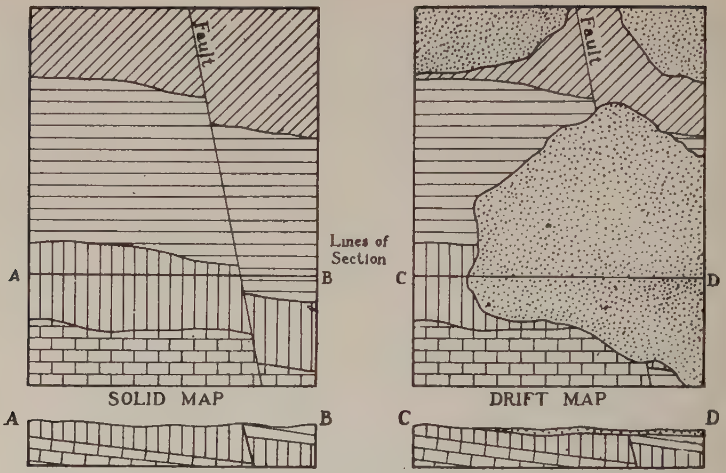
Fault
Fault
Lines of Section
A
B
C
D
SOLID MAP
DRIFT MAP
A
B
C
D

FIG. 165.—GEOLOGICAL MAPS, "DRIFT" AND "SOLID."

Diagrams illustrating the difference between a map showing the distribution of the superficial "drift" deposits, and a map of the same area showing the "solid" geology.

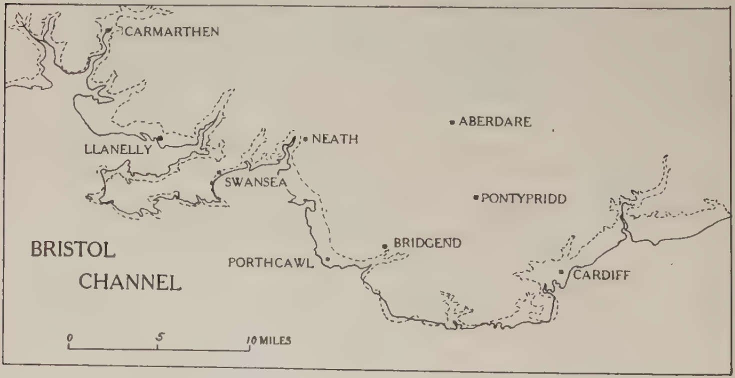
CARMARTHEN
ABERDARE
LLANELLY
NEATH
SWANSEA
PONTYPRIDD
BRIDGEND
BRISTOL
CHANNEL
PORTHCAWL
CARDIFF
0
5
10 MILES

FIG. 166.—MAP ILLUSTRATING THE COAST LINE OF SOUTH WALES. DURING "RAISED BEACH" TIMES.

The probable position of the coast of "raised beach" times is represented by the broken line: in general, it was further inland than at present, but in a few places it was a little in advance of the present coast line.

The amount of new land exposed in geologically recent times is small, and in no case does it include parts of the open sea in which limestone deposits had accumulated.

[11], and particulars of the maps published by the Geological Survey will be found in a List published by the Stationery Office [12].

Limestones of recent origin.—Conditions during the Glacial Period were not, as we have seen, favourable to limestone formation, and their effect upon previously formed rocks has also been discussed; it only remains to refer to the calcareous rocks and limestones that have been formed in comparatively recent times or that are still in process of formation, and also to some of the products of limestone weathering.

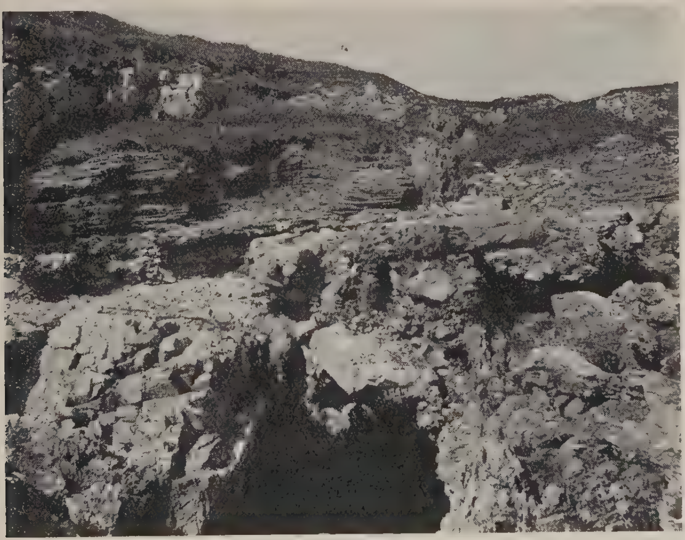

FIG. 167.—A "RAISED" BEACH.

A raised beach at Caldy Island, consisting of pebbles with sand resting on the Carboniferous Limestone, about eighteen feet above present sea level. (*Photo F.F.M.*)

Although in post-glacial times there have been changes in the relative level of land and sea—indicated, for example, by the "raised beaches" and "submerged forests" found on many parts of the coast—the movements have been comparatively small; they have not resulted in the exposure of parts of the sea floor where calcareous ooze had accumulated, so that in this country there are no recent limestones of marine origin. This is illustrated in *Figs.* 166 and 167; the former of these shows the comparatively small addition to the coast-line of part of South Wales produced by the last widespread uplift to which our islands were subjected, and in the latter the shallow water shore-deposits that were raised above sea level are depicted.

The oolitic oozes of the Bahama Islands, the *Globigerina* ooze of the deep ocean floor, and the calcareous accumulations associated with coral reefs, have already been mentioned, and for further information concerning them, reference should be made to the works enumerated in the list of references at the end of the present chapter [13-15].

Although changes in elevation or in drainage may have resulted in the disappearance of a few lakes or ponds in this country, no important modern freshwater limestones, other than local patches of calcareous shell marl such as those mentioned on page 304, have been exposed, and practically all the recent calcareous materials have been produced as a result of the precipitation of calcium carbonate under terrestrial conditions.

We have seen that, owing to its solubility in water containing carbon dioxide, calcium carbonate is present in practically all waters that have come into contact with rocks containing calcium-bearing minerals, while other salts of calcium, such as the sulphate and the chloride, may also be present. The amount of calcium carbonate held in solution is small, varying from 0.03 per cent. in springs issuing from limestone rock, and 0.0116 per cent. in the water of the Thames that flows for a considerable distance over chalk, to practically nothing at all in streams that flow over non-calcareous rocks. Some of the dissolved calcium carbonate may reach the sea, and some may be deposited on the way. Of the former, if the amount still remaining in the river water is in excess of that which the sea water can retain (for calcium carbonate is less soluble in sea water than river water) some will be deposited near the shore as a chemical precipitate, and the remainder will pass to the open ocean, eventually to re-appear in the solid state in the skeleton of some marine organisms, or as a chemical precipitate.

Such precipitation takes place on the floor of the Irish Sea near the Isle of Man, where dredging has produced masses of hard greyish limestone in which there are embedded modern shells, indicative of its recent origin. It has been suggested that in this case some of the calcium carbonate may be derived from springs that rise from the sea floor, which is carpeted with glacial gravels in which limestone pebbles are abundant [14].

Similar deposition is taking place off the coast of Mayo

(Western Ireland), and near the mouth of the River Rhone. Where there is an excess of ammonia in sea water due to the decay of organisms, carbonate of ammonia may be produced, which, interacting with some of the dissolved calcium salts, may cause the precipitation of calcium carbonate; precipitation of this kind is taking place on the floor of the Black Sea.

Calcite and Aragonite.—Hitherto, reference has been made to the deposition of " calcium carbonate " as the essential process of limestone formation, but at this juncture it is convenient to draw attention to the fact that calcium carbonate may crystallise as either of two distinct minerals, *calcite* and *aragonite*. Both minerals consist only of calcium carbonate ($CaCO_3$), and both are normally colourless and transparent, but they may be translucent and present greyish or brownish shades. In crystal form (*Fig.* 168), and certain other properties, however, they present marked differences, but these matters cannot be discussed here; reference should be made to a standard text book of Mineralogy [16, 17].

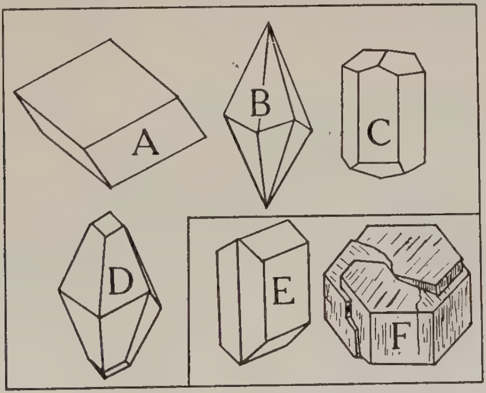

FIG. 168.—SOME OF THE FORMS ASSUMED BY CRYSTALS OF CALCITE AND ARAGONITE. A-D, CALCITE. E-F, ARAGONITE.

The crystal form represented by A is a rhombohedron, by B, a scalenohedron, by C, a combination of a hexagonal prism with a rhombohedron, and by D, a combination of the scalenohedron and a rhombohedron; these all belong to the hexagonal system of crystals, but crystals of aragonite belong to the ortho-rhombic system; they are, however, sometimes combined in such a way (F) as to bear a superficial resemblance to the hexagonal prism.

From the point of view of limestone formation the most important differences are as follows:—calcite is the form in which calcium carbonate is usually deposited in cold or temperate waters; for example, the recent limestone of the Irish Sea floor consists of calcite, as also does the material of stalactites and stalagmites to be described shortly. Aragonite, compared with calcite, is relatively unstable, is more readily dissolved in natural waters, and is more readily converted into dolomite. The shells and skeletons of certain marine organisms consist of aragonite, so that the mineral has been an original constituent of many limestones, but, although in some cases the aragonite still remains as such, under natural conditions it usually changes gradually into calcite, and if artificially precipitated the change may take place in a few hours.

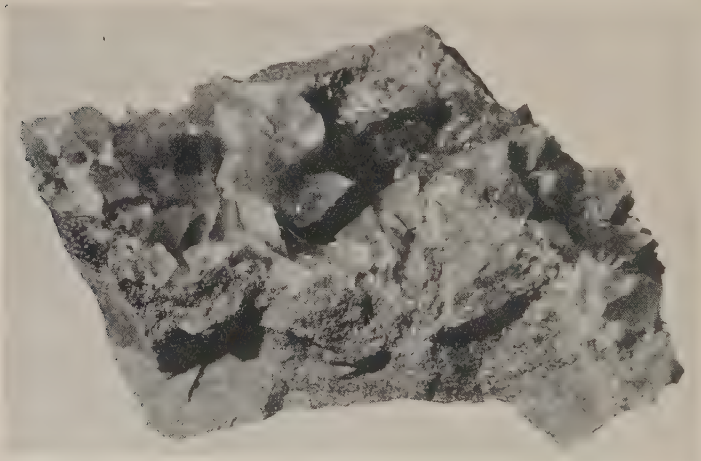

FIG. 169.—CRYSTALS OF CALCITE.

Rhombohedral crystals of calcite lining a cavity in the Carboniferous Limestone; about natural size.

Corals, marine molluscs, and land snails are among the animals that secrete aragonite, while the hard parts of echinoderms, brachiopods, and crustacea, consist of calcite [18]. Recently formed oolitic grains consist, in most cases, if not always, of aragonite, but in the case of the oolitic limestone of the Jurassic and older strata the grains have passed into the condition of calcite.

In the Bay of Naples there are recent limestones formed by the activity of calcareous algæ (*Fig.* 24); of these, some forms, such as *Lithothamnion,* precipitate calcite, while the skeleton of another form, *Halimedes,* contains aragonite [19, 20].

Aragonite is the form in which calcium carbonate is precipitated from tropical sea water or from the water of hot springs, and it can also be made artificially by pouring a hot solution of ammonium carbonate into a boiling solution of calcium chloride. This was demonstrated as far back as 1837 by G. Rose [21], who found that after a time the minute crystals of aragonite pass into rhombohedral crystals of calcite.

In its behaviour towards acids and in imparting the characteristic pinkish "calcium" tinge to the bunsen flame, aragonite resembles calcite, but it may be readily recognised, not only by its crystalline form, but by its superior hardness and higher specific gravity (Specific Gravity of calcite 2.72, of aragonite 2.94; hardness of calcite 3, of aragonite 3.5)*

Calcareous deposits on land.—Returning to the consideration of the calcium carbonate deposited by the water of springs and rivers, we find that, apart from the cases such as those already mentioned, where algæ of various kinds cause deposition, most of the terrestrial calcareous deposits are due to precipitation which may result either from evaporation or from the loss of some of the carbon dioxide by virtue of which the calcium carbonate is held in solution. For example, in the limestone districts of Bosnia, certain valleys tend to become choked with tufa; and in one case, in the River Pliva, tufa is deposited sufficiently rapidly to keep pace with erosion, so that the stream is prevented from lowering its bed to the level of the gorge into which it flows [22].

Another type of simple precipitation takes place in arid regions; for example, A. W. Rogers records the formation of tufa in the Cape of Good Hope, where, in the dry season, evaporation takes place at the surface, so that calcium carbonate is continually brought up from lower levels, forming a solid cementing material in the soil or in the weathered surface rocks [23].

Travertine and tufa.—These forms of calcium carbonate have already been discussed in a general way, and it will be sufficient here to mention one or two instances of their occurrence as "recent" calcareous rocks.

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* Minerals vary in hardness, as indicated by the relative ease with which they may be scratched, or will scratch one another, and a convenient "scale of hardness" was established by the German mineralogist, F. Mohs, more than a century ago. In Mohs' scale, the softest mineral, talc, is 1, and the hardest, diamond, is 10, while quartz is 7.

Calcium carbonate, in the form of travertine and tufa, is often formed as a coating upon stones, twigs, leaves, and similar objects, and some springs and wells owe their fame and popularity to the so-called petrifying character of their waters; one of the

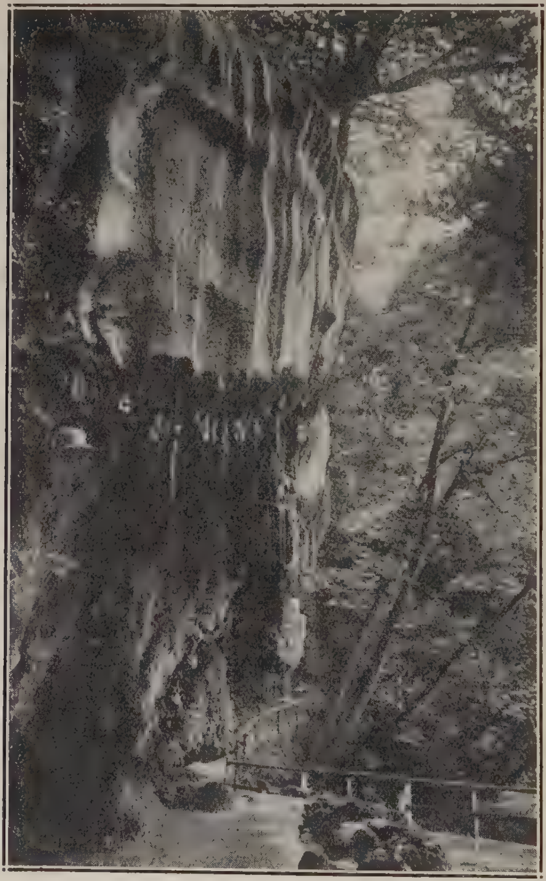

FIG. 170.—THE "PETRIFYING" WELL AT KNARESBOROUGH, NEAR HARROGATE.

Owing to the large amount of dissolved mineral matter present in the water, a layer of hard calcareous material is soon deposited upon objects suspended where the water drips over them.

best known in this country is that at Knaresborough near Harrogate (*Fig.* 170) where the articles of all kinds are suspended in such a way that the water drips over them, and in time invests them with a stony covering (*Fig.* 171), which in this particular case contains more calcium sulphate than carbonate. This process is, however, not true petrifaction, because the object is merely *coated* with mineral matter; it is not actually replaced by or converted into mineral. The water at Knaresborough comes from the magnesian limestone, and that of the "petrifying" well at Matlock in Derbyshire from the Carboniferous Limestone.

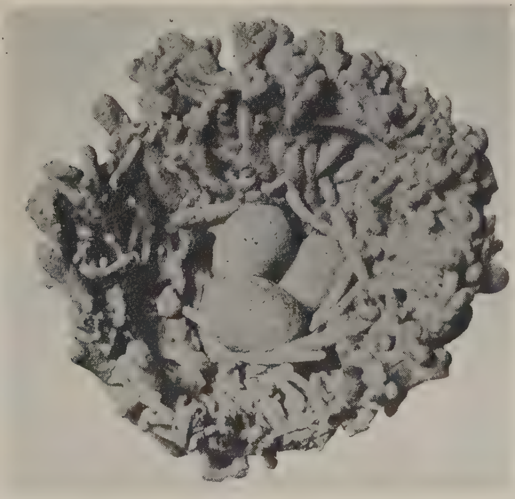

FIG. 171.—A "PETRIFIED" BIRD'S NEST.

An illustration of the work of a so-called "petrifying" well. A mass of twigs, made to resemble a bird's nest and containing clay "eggs," has been suspended in the water until completely coated by calcium carbonate, making what purports to be, but is not, a petrified bird's nest; see Additional Note, page 451.

When freshly deposited, tufa is soft and easily crumbled, and it usually remains so as long as it retains its moisture, so that it is easily cut or dug, but as it dries, it hardens and becomes a light porous rock of considerable strength. The names travertine and tufa are loosely used, and are often regarded as synonymous, but Merrill, the eminent American authority on building stones, regarded the porous varieties as tufa, and the compact varieties, resembling stalagmite, as travertine. Some of the compact varieties are laminated, and when they exhibit suitable tints are used for ornamental purposes under the name "*onyx marble.*"

Onyx marble (sometimes known as oriental alabaster) is so called because of its resemblance to certain varieties of *onyx*, which, however, consists of silica, and is, therefore, very much harder than calcareous onyx-marble. The onyx marbles usually exhibit tints of orange, amber, and green, and are translucent, but although widely distributed, they rarely occur in sufficient quantity to be of economic importance; materials of this kind for making vases, mantelpieces and similar objects, have been obtained from the Tyrol, the Pyrenees, Gibraltar, Algeria, Egypt, and Mexico [24-26].

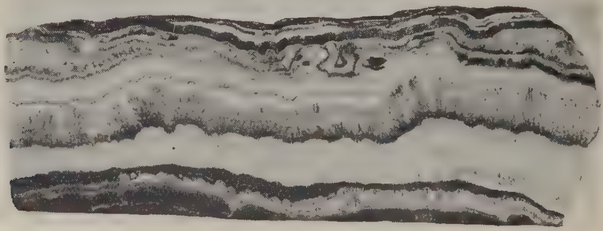

FIG. 172.—STALAGMITE.

A polished section of stalagmite showing the characteristic laminated structure; it will be noticed that the material of some of the thicker layers has crystallised; photograph about half natural size.

Similar in character, are the less highly coloured banded forms of calcium carbonate that constitute the stalagmites (*Fig.* 172) and stalactites found in caves into which calcareous waters have dripped, and, depositing their mineral matter, have formed icicle-like columns pendant from the roof (*Fig.* 25), curtain-like films lining the walls (*Fig.* 170), or hummocky pavements covering the floor; see Additional Note, page 452.

The laminated structure is often beautifully preserved, but subsequent crystallisation may result in its entire obliteration; in such cases the external form, but not the internal structure of the original mass, remains. The stalactitic and stalagmitic deposits of this country have no value as stones, but the interest they impart to the caves where they have been developed—as for example those at Cheddar and other parts of the Mendips and those in

Derbyshire—justifies this brief reference to their origin. They have often contributed much to our knowledge of primitive man and the animals that were contemporary with him, for a layer of calcium carbonate effectively seals and preserves from decomposition or from mechanical destruction, any bones that may have been left on the floor of a cave by animals such as bears and hyenas that used it as a den, or implements and other objects that may have been dropped by primitive man who found it a convenient place of shelter before he learnt to construct a home of wood or of stone (*Fig.* 173).

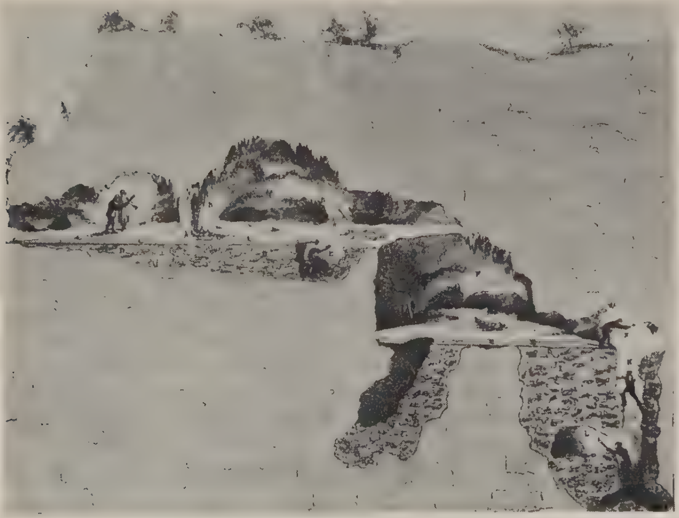

FIG. 173.—CAVES IN LIMESTONE.

Copy of a sketch made by Dean Buckland and reproduced in his "*Reliquiæ Diluvianæ*" (1823), illustrating caves in limestone, with stalactites hanging from the roof, and stalagmitic deposits covering bone-bearing "cave-earth."

Instances of the deposition of layers of calcium carbonate from water heavily charged with that substance are sometimes found in pipes that convey mine-waters. One of the most interesting of these is the "Sunday Stone" of Dean Buckland; it was obtained from a pipe draining a coal mine near Bristol, and was described in the Philosophical Transactions of the Royal Society in 1773. The material had been deposited in layers, some of which were light in colour, but the majority were dark; the explanation given was that the dark layers were deposited on days when the mine was being worked and the men by their operations made the water dirty, while on the days when no work was done the water ran clear and deposited a white layer of pure calcareous material [27].

A similar record came from a colliery in the north of England; a section of the stalagmitic material that accumulated in the pipes was marked with rings of grey and white, the former representing deposits made during the day time when the waters were disturbed, and the latter, deposits made at night when no work was in progress. The rings were for the most part equal in thickness, but every sixth light coloured ring was about three times as thick as the others—representing the week-end interval, Saturday afternoon and Sunday.

In this country travertine and tufa are found associated with the Carboniferous Limestone, the Oolites, and the Chalk, but rarely in great abundance. The localities include Matlock in Derbyshire, Caerwys and other places in North Wales, Dursley in Gloucestershire, and Totland Bay in the Isle of Wight.

The stone was known to the Romans who came to this country, and it is frequently found in the remains of the buildings erected by them; they were, no doubt, already familiar with such material, for it had been used in the Colosseum and many other buildings in ancient Rome.

Being, like the Beer Stone, light and strong, tufa was at one time used for arches and vaulted ceilings, and in districts where it was abundant, whole buildings were constructed of the rock, but at the present time it is scarcely used at all except for rockeries and in decorative gardening.

One of the best known of the tufas in this country is that occurring near Dursley in Gloucestershire [28]. It has been deposited from the water of springs that issue from the Marlstone, one of the divisions of the Lias. What is probably one of the earliest references to its use is found in the account of John Leland's travels up and down the country in the early part of the sixteenth century—between 1535-1543. He wrote of " A quarie of tophe stone . . . whereof much of the Castelle [that is Berkeley Castle] was buildid."

A later writer, Sir R. Atkyns, in *The Ancient and Present State of Gloucestershire* (1712) described it as a " rock of stone . . . without any chop or slit, of an incredible durrance, yet soft to be hewen; it is by the inhabitants called Puff Stone. The walls of Berkeley Castle were built in this stone; and though they are about 600 years standing, yet no decay can be perceived"; towards the end of the eighteenth century, Ralph Bigland, in his *Historical . . . Collections relating to Gloucestershire* (1791), stated that owing to its lightness and durability the stone was much used for "vaulting ceilings, set between the Ribs of springing arches," adding, "The High Choir of the Cathedral at Gloucester is a fine specimen of this application of it."

Near Caerwys in North Wales there are a few patches of tufa, some of which are unusually thick. The material was deposited from water (that of the River Wheeler, or Chwiler) highly charged with calcium carbonate derived from the Carboniferous Limestone. It is of comparatively recent origin, and the river has since deepened its channel, cutting ravines in the tufa, and exposing it to a depth of from 18 to 20 feet without reaching the base. Generally soft enough to be dug with a spade, it hardens on exposure, and contains impressions of marsh plants and the shells of land and freshwater molluscs [29].

The rapidity with which such deposits may form is illustrated by an occurrence near Prestatyn in Flintshire. The material consists of white calcium carbonate enclosing shells and twigs, and was deposited from the water of a spring that was formerly used to work a mill (Felin Nant), but owing to mining operations the springs failed and the formation of tufa was brought to a close [30].

Other tufa deposits in North Wales have also been described, but the material does not appear to have been put to any other use than the making of rockeries [31].

Tufa occurs in association with the Kentish Rag at East Malling in Kent, and was used in the walls of the Church at that place and also in the early Norman St. Leonard's Tower. It occurs in many places along the foot of the Tabular Hills in Yorkshire, and was used locally for garden decoration; blocks from the upper part of Forge Valley were used for the tanks of Scarborough Aquarium [32].

Recent shell-deposits.—Along some parts of the coast (especially in the west) there are accumulations of shells or shelly debris in sufficient quantity to be regarded as potential limestones: in some cases, as a result of the action of percolating water, the lower layers of such deposits have been converted into compact material not unlike some parts of the Pliocene Crags. An example of a recent shell-deposit is to be seen at the northern end of the

Scottish island of Iona: the material, which covers quite a large area, consists largely of finely broken shell fragments and was probably formed by the action of wind on the material of a raised-beach. The sand, which contains about 70 per cent. of calcium carbonate, acts as a fertiliser when blown over the adjacent country, and it is suggested that it might also be shipped to neighbouring coasts for the same purpose [2, p. 100]. A recent shell-deposit on the Irish coast was described on page 40.

Recently formed calcareous deposits of freshwater origin are also known; for instance, a few miles west of Welshpool a shelly marl occurs in the alluvium deposited from a small lake that existed some time after the close of the glacial period, but has long since been drained. The marl, which is greyish white when wet but chalky looking when dry, contains about 80 per cent. of calcium carbonate, and is attributed by Professor W. J. Pugh [33] to the decay of lime-secreting plants and the shells of freshwater molluscs that thrived at a time when the waters of the lake were clear: at other times, when the stream that entered the lake brought down much mud, clay was formed, and this eventually covered up the marl, thus leading to its preservation.

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PART III.

LIMESTONE IN RELATION TO SCENERY, AGRICULTURE, WATER SUPPLY, AND INDUSTRY.

CHAPTER XIII.

LIMESTONE, SCENERY, AND AGRICULTURE.

> "Now . . . I will speak somewhat of the naturalle helpes which are found in the countrie to better the lande . . . the cheffest thereof I recon the lyme."
>
> GEORGE OWEN, in "*Description of Penbrokshire*" (1603).

Limestone and scenery.—Regions where limestone forms the surface-rock over comparatively large areas have a characteristic scenery of their own. This is due in part to the structural features of the rock itself, and in part to its solubility in atmospheric waters. Limestone often occurs in beds that are relatively thick (*Fig.* 174), because, on the floor of the open sea, where, as we have seen, many of our most extensive limestone formations were laid down, changes due to variations in the direction of currents or to the incoming of other types of deposit would be less frequent than in the shallow water near to the coast, and it is to such changes and the alternation of such changes that stratification is normally due. Joints are developed (*Fig.* 111) as in other strata, and these, combined with the thickly bedded characteristics, are responsible for the massive wall-like cliffs and precipices that are so frequently developed in limestone districts; indeed, limestones such as the Carboniferous or those of the Lias give rise to some of the most impressive scenery of the British coast (*Figs.* 129, 130, 154, 175). Where the rock is comparatively soft, as in the case of the chalk, steep cliffs are developed along the coast (*Figs.* 145, 176), but inland, the processes of weathering produce rolling downs and smooth-sided valleys; in cliffs and railway cuttings the chalk often appears to be homogeneous, and only the bands of flint make it possible to distinguish its bedded character; see *Fig.* 145.

In Carboniferous Limestone country, on the other hand, where the rock is harder, the features of the ravines or the cliffs are determined by the strong bedding planes and the well defined joints; crags and precipices scar the hills (*Fig.* 178) and the valleys are often steep-sided ravines.

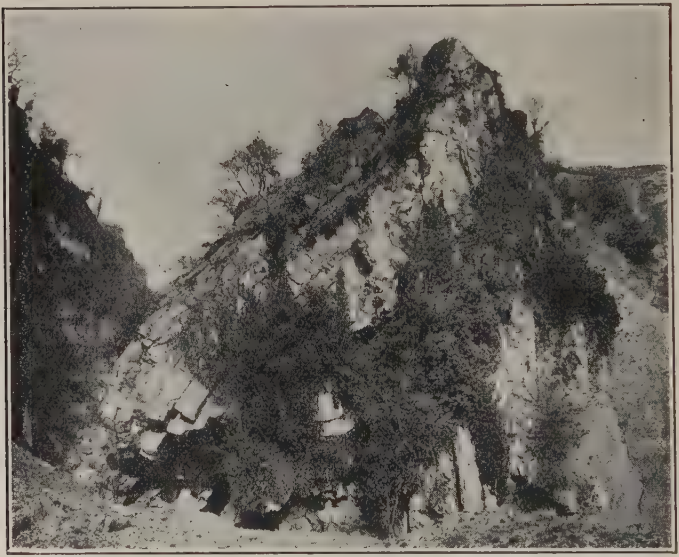

FIG. 174.—CARBONIFEROUS LIMESTONE, NEAR GLYN NEATH, GLAMORGAN.

The rock is known as Bwa Maen (bow or arch rock) and is an example of a sharp anticlinal fold in thickly bedded limestone. (*Photo I.V.E.*)

The characteristic features of "hard limestone" scenery—wall-like precipices, curiously fretted pinnacles, and jagged peaks—are well developed in dolomite rock also, but there are not, in this country, sufficiently large areas of pure dolomite for this to be as apparent as it is in the Dolomite Mountains of the Eastern Alps, and in parts of Switzerland [15].

Owing to the solubility of the rock and its fissured character, the surface in limestone districts tends to be comparatively dry, unless there is an impervious mantle of drift or other superficial deposit. Rain water, instead of flowing over the surface in brooks and rivers, makes it way through pores and crevices in the rock, and travels, in large measure, underground (*Fig.* 177). In the Chalk districts, for example, not only is the surface comparatively dry, supporting little other than the grass that forms the characteristic turf of the downs, but even the valleys or combes are often streamless, and, owing to the porosity of the rock, and the readiness with which water drains away from the surface, farm- and cattle-ponds have often to be lined with clay in order to render them watertight.

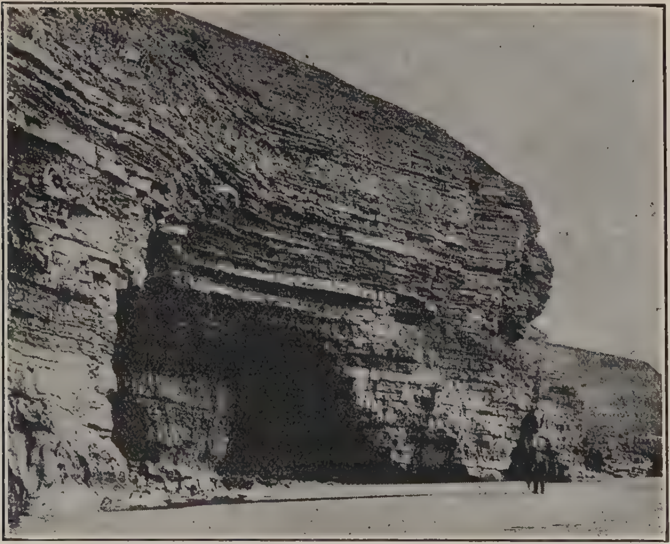

FIG. 175.—LIMESTONE CLIFFS AT SOUTHERNDOWN, GLAMORGAN.

The lower part of the cliff in the left-hand corner of the photograph consists of Carboniferous Limestone, which, owing to the dip of the strata soon passes beneath the level of the shore; the remainder of the cliff is of Lower Lias (limestone with thin beds of shale), and owing to the well bedded and well jointed nature of the rock, wave action has resulted in the development of large caves. (*Photo F.F.M.*)

At a depth beneath the surface that varies with the supply of water, the rock will, of course, be saturated, and in wet weather the saturation-level may rise sufficiently high to reach the valley floors, giving rise to temporary streams or "bournes," such as the "nailbournes" of Kent, and the "winterbournes" of Dorsetshire and Wiltshire; in the two last named counties, "winterbourne" forms parts of the name of at least 24 villages, such as

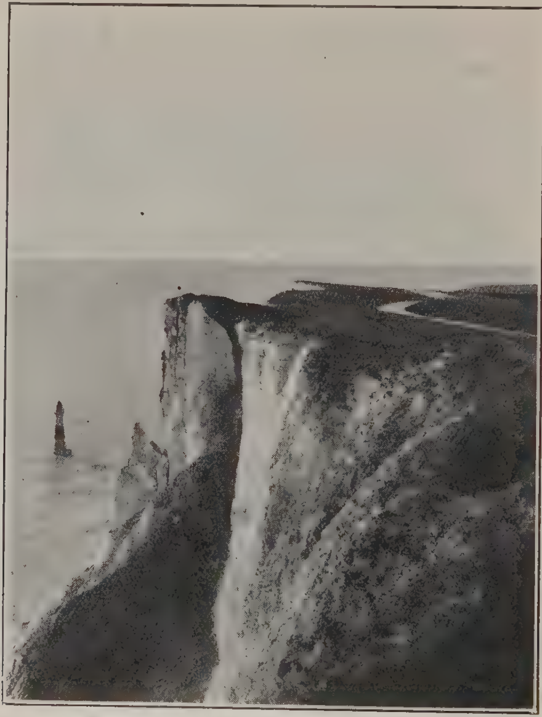

FIG. 176.—CHALK CLIFFS ON THE SUSSEX COAST.

The cliffs consist of Upper Chalk with flints, bands of nodules of which are visible in the photograph. Although chalk is comparatively soft the cliff maintains a steep precipitous face because the waves attack its base and give rise to falls of rock. (*Photo Photochrome Co., Ltd.*)

Winterbourne Abbas and Winterbourne Stoke. Similar intermittent streams in the Chalk districts of Yorkshire are called "gipseys"; for example, Gipsey Race is a stream which rises at Weaverthorpe in the East Riding, flows for 3 miles underground, and re-appears at Wold Newton.

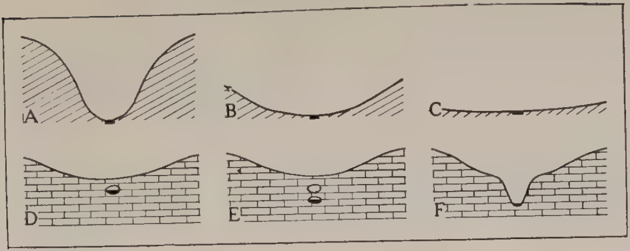

FIG. 177.—DIAGRAM ILLUSTRATING RIVER VALLEYS IN DIFFERENT KINDS OF ROCK.

Ideal sections across valleys in different kinds of rock and at various stages of development.

A—C., conditions in a rock such as sandstone or clay where the valley is gradually widened and deepened as erosion of the sides and floor proceeds. D—F., conditions in a limestone district where the water tends to flow underground and produce subterranean channels, the collapse of the roofs of which give rise to gorges.

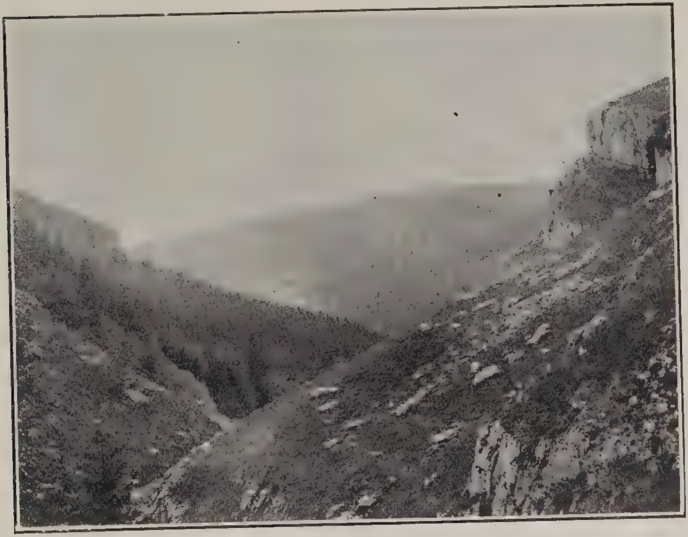

FIG. 178.—A VALLEY IN A LIMESTONE DISTRICT.

The Carboniferous Limestone of the Eglwyseg Rocks near Llangollen, showing the steep precipices due to the jointing of a massive limestone, and the screes resulting from the action of the agents of weathering that have dislodged fragments of rock from the exposed faces. (*Photo F.F.M.*)

In the case of a clay or a sandstone, weathering, and the work of soil-dwelling animals and of plant roots, tend to reduce the surface layers of the rocks to a fragmentary and friable condition, and under certain circumstances may give rise to relatively thick accumulations of soil, but rain water that falls on the chalk slowly dissolves the calcareous matter as it percolates through the rock, and, in the absence of glacial or other superficial material, the soil over chalk consists almost entirely of the very scanty residues of insoluble matter and flints that may have been present in the rock that has been removed by solution. On this account, paradoxical as it may seem, soils resting upon and derived from the Chalk are often so deficient in calcium carbonate as to require top-dressing with lime or with chalk.

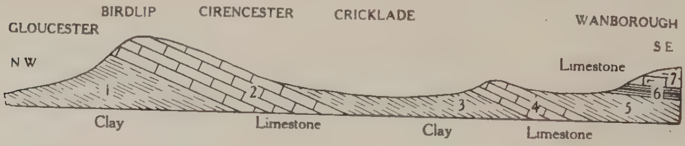

FIG. 179.—DIAGRAMMATIC SECTION OF THE STRATA ALONG THE COURSE OF THE ERMINE STREET.

The section extends from near Swindon to Gloucester, and the length represented is about 32 miles; it shows the escarpments formed by the Jurassic Limestones and the Chalk. (1) Lias (mainly clay), (2) Inferior Oolite, Great Oolite and Cornbrash (mainly limestone), (3) the Oxford Clay, (4) Corallian Beds (largely limestone), (5) Kimmeridge Clay, (6), Lower Greensand and Gault (mainly clay), (7) Chalk.

Sometimes the chalk is locally concealed beneath a layer of "clay-with-flints"—a mixture of red clay or loam with an abundance of flints; such areas often support beech woods and may be capable of cultivation [14]. It was formerly supposed that the clay-with-flints resulted from the removal in solution of a vast thickness of chalk, of which it represents the insoluble material, but Jukes-Browne [4] showed that although the flints were derived from the chalk, most of the argillaceous material represents the debris of Tertiary strata (clays of Eocene age) that have been almost completely removed by denudation. He concluded that the areas of clay-with-flints were formerly more numerous and larger than at present. Red ferruginous soils (known as *terra rossa*) made up of the insoluble residues of limestone, are extensively developed in south-eastern Europe, as for example, n the Karst country, east of the Adriatic Sea, where the rainfall s so scanty that the insoluble material is not generally washed nto streams and carried away.

The scenery of the Jurassic outcrop is too variable to be lescribed in a few words, because of the great variety of lithoogical types that are represented. In the Cotteswold country, and other places where the oolites are well developed, the limestone bands form conspicuous escarpments—hill ridges with steep slopes to the north-west and gentle dip-slopes falling away to the south-east—between which are tracts of low ground formed from the clays and the comparatively soft sandy rocks (*Fig.* 179), while in Somerset and Dorset, the outcrops of the Forest Marble and of the Bath Oolites give rise to escarpment slopes and flat topped hills, alternating with the valleys formed from the Fuller's Earth and other clays.

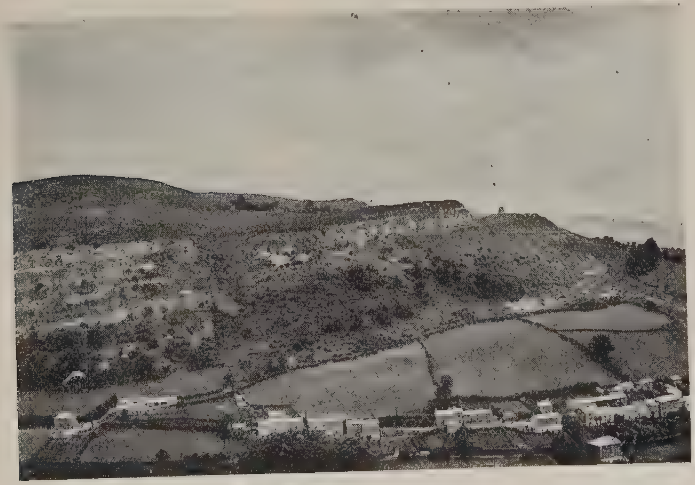

FIG. 180.—THE CARBONIFEROUS LIMESTONE AT CLYDACH, NEAR ABERGAVENNY.

The hard Carboniferous Limestone, which is inclined gently to the left and gives rise to the rocky escarpment, has resisted wearing to a greater extent than the marls of the Old Red Sandstone which occupy the lower cultivated ground. (*Photo W.E.H.*)

In Yorkshire, the lower Oolites generally give rise to undulating moorland intersected by deep valleys, along the sides of which hard beds outcrop as lines of crags. The Lower Calcareous

Grit tends to produce flat-topped hills (The Tabular Hills) and tablelands, upon which rest rounded knolls of rock belonging to the upper division of the Corallian beds, while the clay divisions give rise to gently undulating valleys; as usual, however, the actual surface conditions are largely controlled by the "Drift" [5].

The Carboniferous Limestone usually bears a scanty soil (*Figs.* 181 and 193), especially if, as is so often the case in Chalk areas, the soil represents only the insoluble debris of rock that

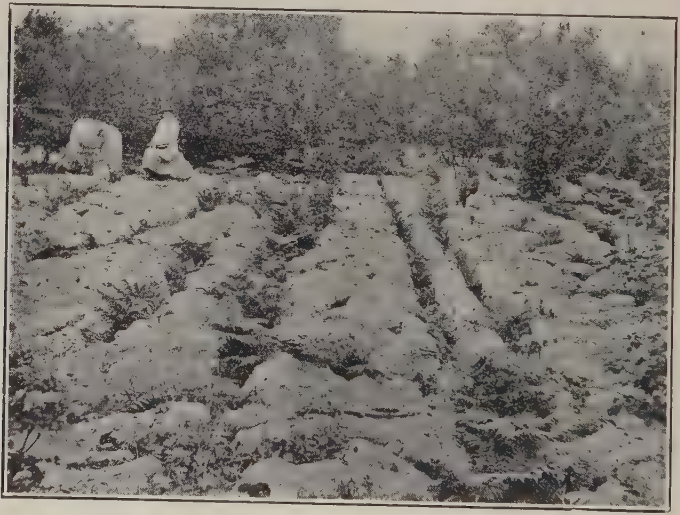

FIG. 181.—A LAND SURFACE OF CARBONIFEROUS LIMESTONE.

The joints have been widened by solution, and the small amount of insoluble material present in the rock has been washed away, so that only in cracks and depressions has enough soil accumulated to permit plants to grow; Beetham, Westmorland. (*Photo F.F.M.*)

has been dissolved away, and no superficial material of glacial or other origin has been introduced. Where the beds lie flat or are only gently inclined, water, collecting in hollows on the surface, gradually dissolves the rock along the joint planes, and gives rise to fissures that may eventually become very deep (*Fig.* 182). These may remain open or may be partially filled by soil, and they often contain luxurious growths of ferns and other plants, while the flat surface between them may remain practically without soil; see *Fig.* 181 and Additional Note, page 453.

In upland regions the almost bare rocky surfaces give rise to bleak moorlands, but the valleys in the Carboniferous Limestone districts constitute some of the most picturesque scenery of our country. The collapse of the roofs of former underground water courses may give rise to deep ravines with cliff-like sides of bare rock (Cheddar Gorge, for example, *Fig.* 183), or to steep wooded slopes (as in some of the Derbyshire Dales). The gorges of the Wye near Chepstow and of the Avon near Bristol occur where the rivers flow across the Carboniferous Limestone, and because of the tendency of the rock to give rise to hilly country with steep scarps, inland cliffs, and ravines, it was originally known as the Mountain Limestone; as such it is represented on many of the older geological maps.

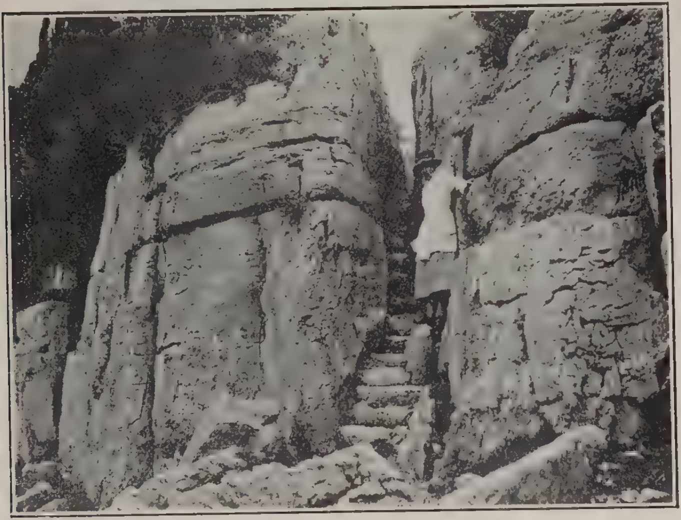

FIG. 182.—THE EFFECT OF SOLUTION UPON LIMESTONE.

Joints in thickly bedded Carboniferous Limestone that have been widened by solution, giving rise to deep narrow fissures; Beetham, Westmorland. (*Photo F.F.M.*)

Owing to the solubility of the rock, by reason of which the cracks along which water flows are enlarged and so provide channels for its still more rapid draining away, much of the water in a Carboniferous Limestone district makes its way underground, and many of the stream-courses are, like those of the Chalk country, dry except in wet weather (*Fig.* 184); one result of the underground movement of the water is that, in such a region, tributary streams are comparatively rare and the hillsides are not scored with the channels of tumbling brooks as is usually the case where insoluble rocks occur at the surface (*Fig.* 185). The tendency of water to pass underground in well jointed lime-

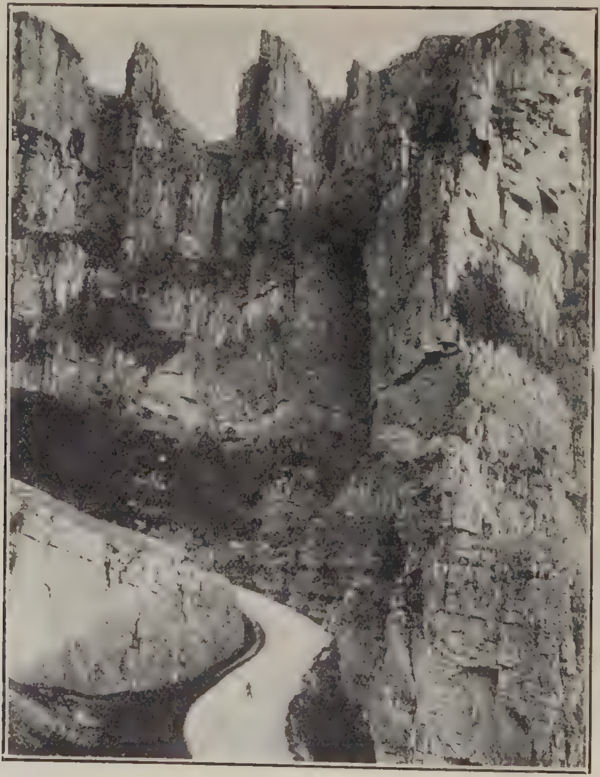

FIG. 183.—INLAND CLIFFS OF LIMESTONE.

Cliffs of Carboniferous Limestone forming the sides of a ravine—Cheddar Gorge, Somerset. The gorge has resulted from the collapse of the roof of an underground water course. (*Photo Frith and Co., Ltd.*)

stones like the Carboniferous Limestone is illustrated in *Figs.* 186-189.

Near Ystradfellte in Brecknockshire, certain streams flow beneath the surface for considerable distances where their courses lie over the outcrop of the Carboniferous Limestone. *Figs.* 186 and 187 show the disappearance of the River Mellte into a cave-like opening at the foot of a high limestone cliff, and its re-appearance after an underground course of more than a furlong, while *Figs.* 188 and 189 illustrate a similar phenomenon on the neighbouring River Neath, which, at a place called Cwm Pwll-y-Rhyd plunges into a deep chasm that stretches across the bed of the stream, so that except for the water that remains stationary in the basin-like pools with which the bed abounds, the channel with its smooth waterworn sides is dry unless heavy rains bring more water than the underground passage can convey.

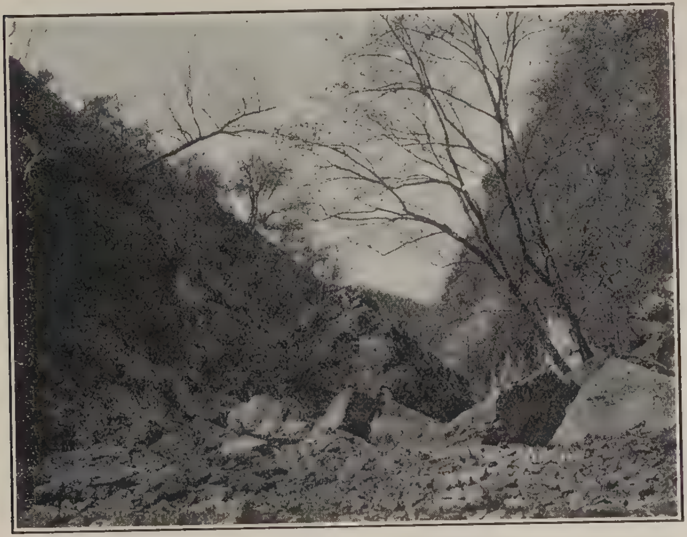

FIG. 184.—A DRY RIVER-BED.

The bed of the Sychrhyd River near Glyn Neath, Glamorgan, where the stream course is over limestone and most of the flow is underground. (*Photo I.V.E.*)

An interesting example of this phenomenon occurs in North Wales at a place where the outcrop of Carboniferous Limestone constitutes the watershed between the Rivers Dee and Clwyd. As so often happens on the limestone, some of the streams flow underground, and the water of one such underground stream nea

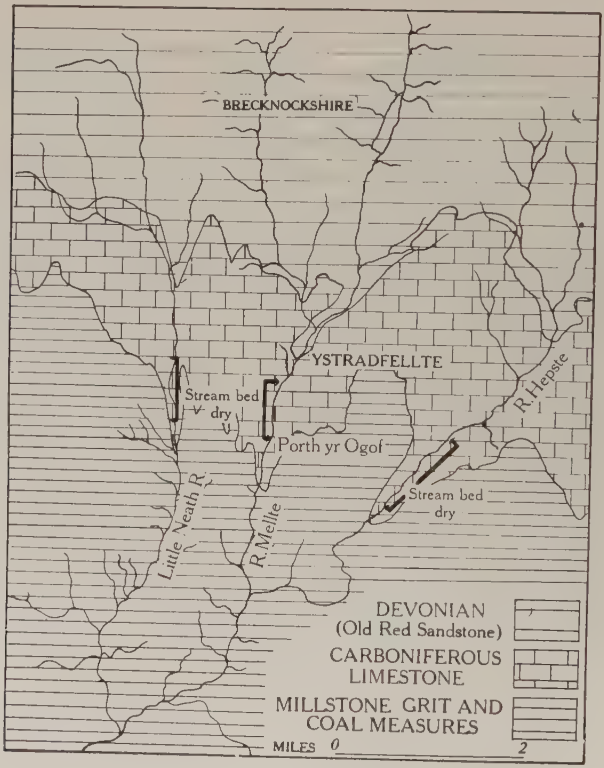
BRECKNOCKSHIRE
YSTRADFELLTE
Stream bed dry
Porth yr Ogof
Stream bed dry
Little Neath R.
R. Mellte
R. Hepste
DEVONIAN (Old Red Sandstone)
CARBONIFEROUS LIMESTONE
MILLSTONE GRIT AND COAL MEASURES
MILES 0 2

FIG. 185.—MAP ILLUSTRATING THE UNDERGROUND COURSES OF RIVERS IN A LIMESTONE DISTRICT.

Near Ystradfellte in Brecknockshire, a number of small streams tend to flow underground when they reach the Carboniferous Limestone. They do not flow underground over the whole of the limestone outcrop because the rock is, in part, concealed beneath a covering of drift.

Siamber Wen makes its way into the River Alun and eventually into the Dee which reaches the sea beyond Chester, while, when after heavy rain the old dry bed is occupied, the surface water flows in the opposite direction from that in the subterranean channel, and drains into the Chwiler (or Wheeler) River that enters the Clwyd and reaches the sea near Rhyl. The Alun itself also flows underground for a considerable distance near Cilcain in Flintshire, but there is no obvious cavity into which it disappears; the water simply drains away among the stones of its bed, which is dry except after heavy rain.

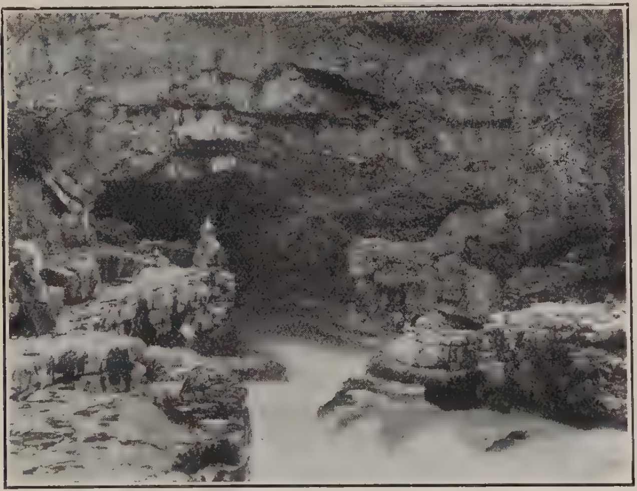

FIG. 186.—A RIVER ENTERING A CAVERN IN LIMESTONE.

The River Mellte in Brecknockshire flows for part of its course in underground passages resulting from the solution of the Carboniferous Limestone; at Porth-yr-Ogof it enters a wide low cave at the bottom of a deep gorge, and it emerges from another cave-like opening a furlong lower down the valley; see Fig. 187. (*Photo F.L.*)

Swallow-holes and limestone " pipes."—Near the edge of the Carboniferous Limestone outcrop the surface is often dotted with circular depressions (*Fig.* 191); some of them are shallow and saucer-like, while others are deep and funnel-like, and they owe their origin to the collapse of the roofs of caverns that have been produced as a result of the removal in solution of part of the underlying rock (*Fig.* 190). In cases where the roof has collapsed completely and there is direct communication between the surface and the underground cavities, the water of small streams flowing into the holes disappears at once, and such cavities are known as "swallow-holes." They are well displayed, for example, near the junction of the Millstone Grit and the Carboniferous Limestone in Brecknockshire, and along the Mendip Range they occur where the main mass of the Carboniferous Limestone gives place to the somewhat impure limestones and shales that constitute the division known as the Lower Limestone Shales. In the latter district the highest ground is formed of Old Red Sandstone, a water-bearing formation, and, where it gives place to the less permeable Lower Limestone Shales, water is thrown out from it in the form of springs; from these, small streams flow across the shale outcrop, and, on reaching the Carboniferous

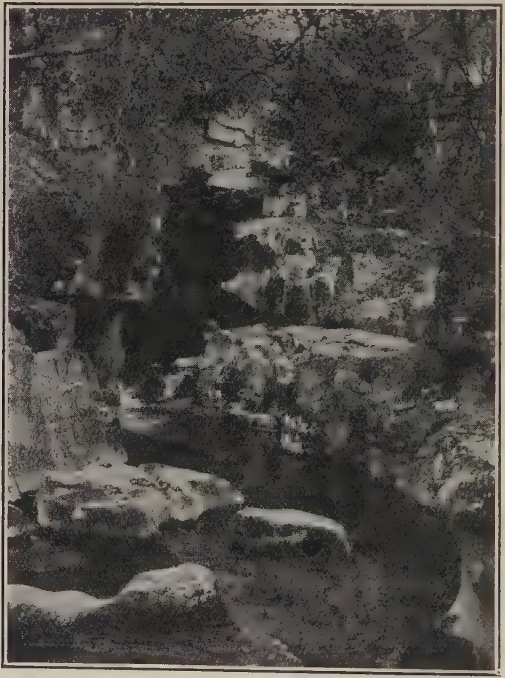

FIG. 187.—A RIVER EMERGING FROM A LIMESTONE CAVERN.

The River Mellte, Brecknockshire, flowing from the lower end of a tunnel-like cavern in the Carboniferous Limestone.

Limestone proper they tend to disappear; some of them are known to pass for long distances underground. Similar phenomena are seen in Derbyshire (for example, Elden Hole near Castleton, and Skipton in Yorkshire). The stream flowing from Malham Tarn, also in Yorkshire, sinks underground as soon as it leaves the outcrop of the Silurian strata (on which the Tarn is situated), for the well jointed and soluble Carboniferous Limestone [6].

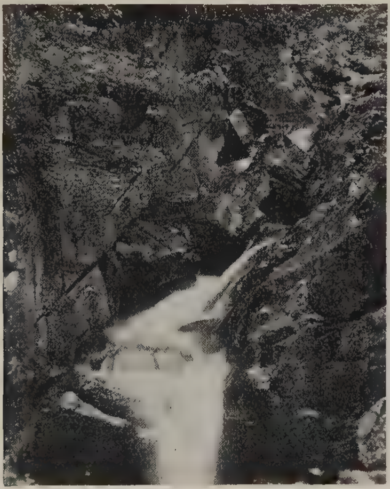

FIG. 188.—A RIVER DISAPPEARING INTO A FISSURE IN LIMESTONE.

The River Neath at Cwm Pwll-y-Rhyd in Brecknockshire flows over the Carboniferous Limestone and disappears into a fissure in its bed.

Swallow-holes (also known as swallets or sink-holes) are a characteristic element in limestone scenery and are not confined to one area or to the Carboniferous Limestone. They are well-displayed in the limestone district of Kentucky, where there are also large caves [7], and in this country they are seen, for example, in association with the Magnesian Limestone near Ripon, the Lincolnshire Limestone near Benefield in Northamptonshire, the Kentish Rag near Maidstone, and along the junction between the Chalk and the Tertiary strata. Some of the latter were described by the late W. Whitaker in his Memoir on the Geology of London [9]; water flowing over the lower Eocene beds, which are for the most part impermeable, tends to sink underground on reaching the chalk, making, in time, as in the case of the Carboniferous Limestone, distinct funnel-like or saucer-like hollows. In many cases, as for example near Potters Bar, swallow-holes in the Chalk take all the water in dry weather but as the flow increases during wet spells the channels beyon the swallets become occupied by water, and there exist, for time, continuous surface streams [8].

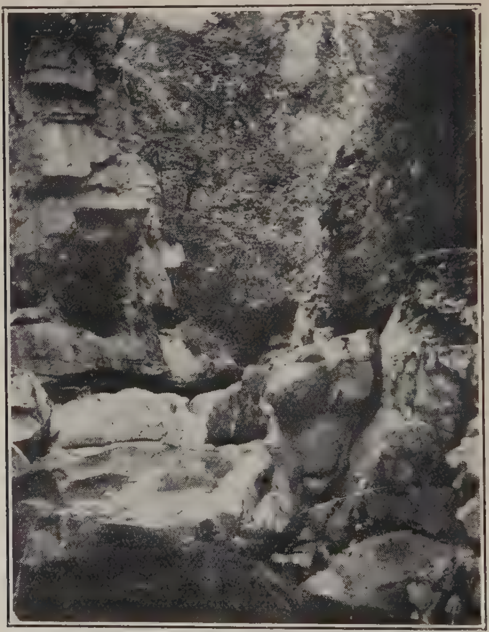

FIG. 189.—A LIMESTONE GORGE.

The River Neath, at Cwm Pwll-y-Rhyd flows, like many other rivers, in underground courses when it crosses the Carboniferous Limestone. At the spot illustrated, most of the flow is underground, and except for local pools, the water-worn rocks at the bottom of the gorge are dry.

Just as the strata resting on the Carboniferous Limestone are sometimes let down into cavities that have resulted from the solution of the rock (see *Fig.* 190), so the surface of the chalk, where it is covered by Eocene sands or by gravels, exhibits more or less vertical gravel-filled shafts or " pipes " due to the solution of the calcareous rock and the collapse of superincumbent material to fill up the space so formed (*Fig.* 192) [9-13].

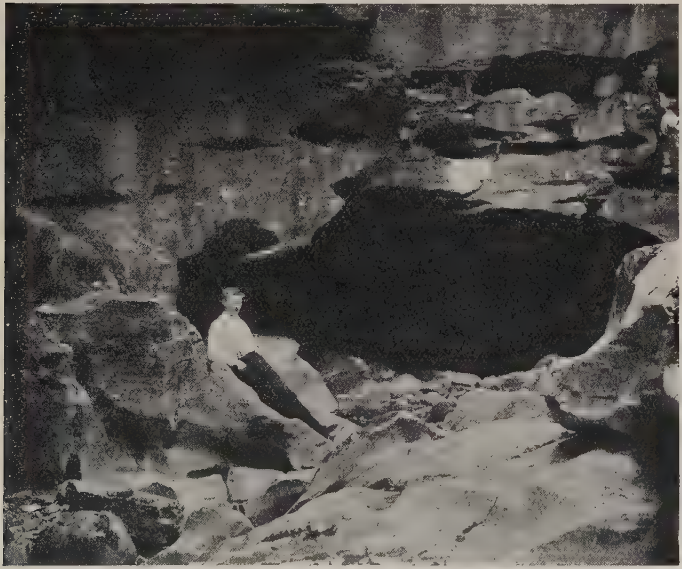

FIG. 189a.—A SUBTERRANEAN WATERCOURSE IN LIMESTONE.

The water-worn tunnel-like opening from which the River Neath emerges after its underground course in the Carboniferous Limestone.

The tunnel lies at a lower level than the gorge illustrated in Fig. 189, and the photograph was taken in dry weather: in wet weather the channel is unapproachable. (*Photo G. T. Flook.*)

From observations made during the construction of a branch railway near Watford, however, it has been shown that some at least of the " pipes " in the Chalk are not the result of solution that produced cavities into which debris from above has fallen [13]. It was found that sections such as those illustrated in *Fig.* 192 do not necessarily indicate conical " pipes " of gravel,

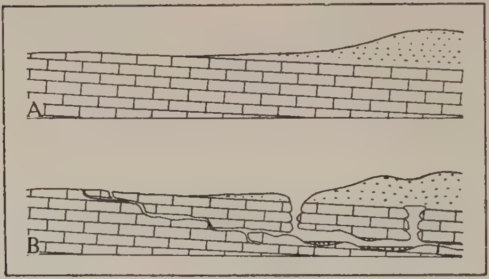

FIG. 190.—DIAGRAM ILLUSTRATING THE FORMATION OF "SWALLOW HOLES."

The upper section (A) represents sandy strata resting upon inclined beds of limestone, and the lower section (B) represents the underground passages and cavities produced where the limestone has been dissolved by percolating water, and into which parts of the overlying strata may fall and be preserved from denudation long after all other traces of the beds have been moved away.

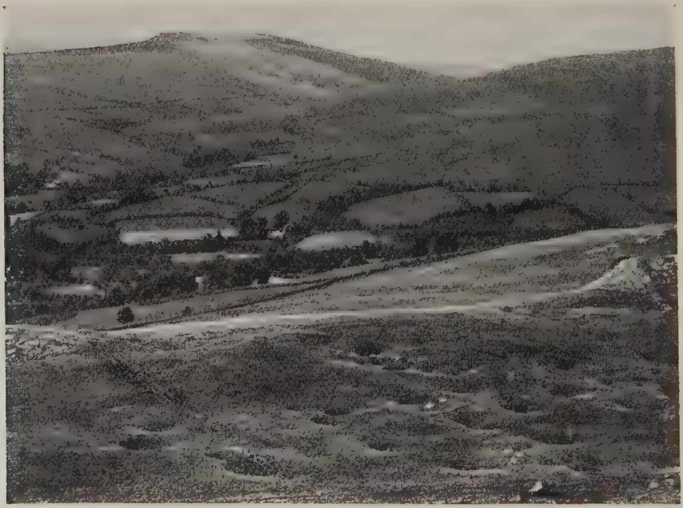

FIG. 191.—"SWALLOW HOLES" ASSOCIATED WITH THE CARBONIFEROUS LIMESTONE.

Shallow circular depressions due to the collapse of cavities (produced by solution) in the Carboniferous Limestone, near Ystradfellte, Brecknockshire.

but may cut across long narrow grooves in the surface of the chalk. These grooves were formed towards or soon after the close of the glacial period, when, owing to the melting snows and the torrential rains, much water flowed down the slopes of the Chiltern Hills, scouring away material that had been decomposed along joints or along old water courses, producing parallel furrows in which sand and gravel subsequently accumulated when the water action became less intense. Since then, the River Colne, in the basin of which the area in question occurs, has lowered its bed by erosion, and as a result of the consequent lowering of the water-table the gravel-filled furrows are now dry.

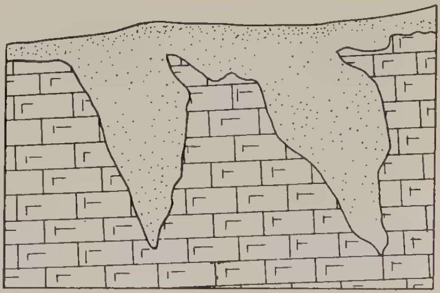

FIG. 192.—" PIPES " IN CHALK.

Diagram illustrating gravel-filled "pipes" in chalk, based upon a section near Foulsham, Norfolk. The pipes, which may vary from 4 or 5 to 10 or 12 feet in depth, are cavities, produced by the solution of the chalk, into which material from above (in this case Pliocene and glacial deposits) has fallen.

The contents of the "pipes" and fissures in the Carboniferous Limestone are sometimes of economic importance. For example, in various parts of North Wales (Caerwys, Nannerch, Cilcain, etc.), there are accumulations of sand and clay filling irregular cavities in the limestone [26], and representing material that, at some time after the close of the Carboniferous Period and before the dawn of the Ice Age, was let down into fissures resulting from the solution of the rock. In times past some of the white clays were used for making pottery and tobacco pipes, and the sands found a place in glass-making.

Similar in general character and mode of origin are sands and clays that occur in the Carboniferous Limestone of Derbyshire (south of Monyash and Youlgreave), and in Staffordshire (the north-western end of the Weaver Hills). The deposits are irregular in shape and distribution, some of them having an area of from 100 to 200 square yards and an unknown depth : they include pale coloured sandy clays with occasional beds of plastic clay, and although usually clean are occasionally stained with oxide of iron. Where bedding or lamination is apparent the layers are inclined towards the centre of the deposit as though the mass had sagged, which, no doubt, has been the case. Some of the material is worked in open pits for use in constructing furnaces, and for making pottery and earthenware [27].

Limestone and agriculture.—The interest and importance of limestone in agriculture lies partly in the nature of the soil to which it gives rise, and partly in its use for improving soils deficient in lime. The subject has received adequate treatment in easily accessible works [16, 17], and only a brief résumé is necessary for the purpose of this account of limestone in general.

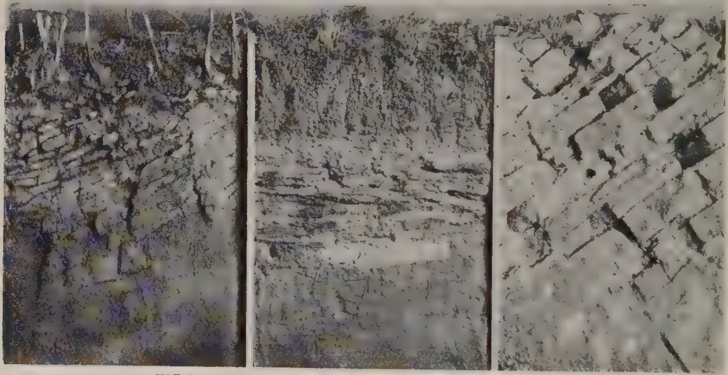

FIG. 193.—ROCKS, SUBSOIL, AND SOIL.

Photograph of a model in the National Museum of Wales illustrating the relation between soil and the rocks from which it has been derived. On the left, a sandstone is seen to pass through a stony subsoil into a sandy soil upon which bracken grows; in the centre is the deep soil resulting from the weathering of an argillaceous rock, and on the right, beds of limestone reach the surface and are almost devoid of soil. This photograph should be compared with Fig. 194.

Water (with its dissolved carbon dioxide and organic acids), plant roots, burrowing animals, and bacteria, all tend, as we have already seen, to decompose or to disintegrate the rocks that make up the surface of the earth, and sub-soil and soil represent stages in the process of rock decomposition.

Soil, and its origin.—The soil may be regarded as the superficial layer of more or less fine grained incoherent material that is cultivated or that is normally penetrated by plant roots (*Fig.* 193); beneath it is the sub-soil, which, under normal conditions, is intermediate in character between the soil above, and the rocks beneath. Exceptions to this are seen where there is (*a*) a covering of glacial deposit (*Fig.* 194), of alluvium or of peat, or (*b*) where there are slopes so steep that loose material is readily washed down by rain or moves under the influence of gravity. In the first of these cases it is the superficial stratum and not the "solid" rock that furnishes the soil, and in the second the soil at any one place may have been derived from rocks occurring at higher levels and will in all probability be of a mixed character.

Since most of the country north of an east-west line connecting the estuary of the Thames with that of the Severn was invaded by ice during the Glacial Period, extensive areas free from glacial drift, in which the soil bears a direct relation to the "solid" rock, are not generally encountered except in the south of England, where many of the soils are of the local (not transported) type.

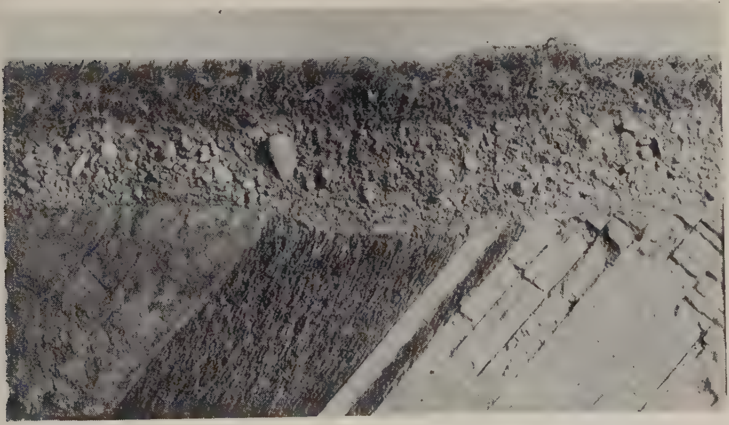

FIG. 194.—THE INFLUENCE OF GLACIAL DEPOSITS UPON SOIL.

In this model, rocks similar to those illustrated in Fig. 193 (sandstone, shale and limestone) are represented as covered by glacially-transported deposits (gravelly clay with pebbles), and the soil which has been derived from the superficial material bears no relation to the "solid" rocks beneath.

We have already seen that the nature of the soil derived from limestone depends largely upon the purity of the rock, because it represents, to a large extent, merely the insoluble residue left after the calcareous material has been dissolved and carried away. The more sandy or argillaceous the limestone, the thicker the soil it will yield, other things being equal, and since "mixed" soils are usually especially favourable to vegetable growth on account of their greater range of physical properties and chemical constituents, impure limestones always yield better soils than those that consist of little else than calcium carbonate.

The advantages of a soil of mixed origin are often seen along the junction of two rock formations: for example, although the Chalk normally yields a somewhat poor thin soil, it rests upon the sandy strata of the Upper Greensand and is in turn succeeded by the clays and sands of the Tertiary formations: in consequence there are, fringing the Chalk outcrop, belts of country where the soil is of a mixed character. The soil where the argillaceous Chalk Marl near the base of the Chalk gives place to the arenaceous Upper Greensand is very fertile, as in the hop-growing district of Farnham and in parts of Wiltshire, while near the upper edge of the Chalk there are soils combining the characteristics of those derived from that rock with those derived from the clays and sands of the Woolwich and Reading Beds, and more fertile than those derived from either of the formations singly; this condition occurs more or less all round the edge of the London Basin (see *Fig.* 38), except where there is a covering of drift.

Soil of mixed origin is also seen along the junction between the Lower Lias and the Middle Lias in Somersetshire; in this region are to be found some of the best orchards in the country. Near Evesham, too, where the clays and limestones of the Lower Lias are patchily covered with sand and gravel, the fertility of the soil induced the mediæval monks to build their Abbey there, and has given rise to a market gardening industry of long standing. At one time grapes were grown in the vicinity, as well as in parts of the Vale of Gloucester [15a].

Mixed soil of another (transported) type is found in many of the tracts of alluvium that occur in the lower reaches of the valleys or fringing the estuaries of rivers. For example, the Severn flows over rocks of all ages from Ordovician to Lias, and the mud it deposits, of a very mixed character, is responsible for the extreme fertility of the Vale of Berkeley, and other areas floored by alluvium.

The soil constituents hitherto mentioned are all of inorganic origin, but organic material is also of importance. Certain plants, for example, the lichens, grow directly upon rocks, such as limestone, and other lowly forms of vegetable life soon develop where weathered rock material exists, and their decay after death produces a certain amount of organic matter, humus, which is a necessary constituent of soil in which plants of higher types are to grow; up to a certain point, the amount of humic material tends to increase with the passage of time, and its effect in improving the quality of soil is very marked; this matter will, however, be referred to again in connection with the artificial application of lime to soil.

The soil in limestone districts. — In this country, the rocks older than the Carboniferous do not include extensive deposits of limestone, and the effect upon scenery and upon agriculture of those that do occur is slight. The limestones in the Silurian System improve the soils where they occur, and the steep ridges of the Wenlock Limestone are often covered with woods while the intervening shale valleys are cultivated.

The Devonian Limestones of Devon and Cornwall yield thin clayey soils, much affected by drought, while the "cornstones" and impersistent bands of limestone that occur in the Old Red Sandstone, especially in the marls of its lower division, supply "lime" to enrich the soils of considerable tracts in Monmouthshire and Herefordshire. They give rise to "brashy" soils, well suited for corn growing—hence the name, "cornstone."

The Carboniferous Limestone of the uplands, as we have already seen, tends generally to produce a thin dry soil, on which sheep farming is more important than agriculture, but in certain situations the outcrop is well wooded; *Fig.* 195.

The (Permian) Magnesian Limestone, which is often sandy, yields a loamy soil; in Durham it provides good grass land, but in Yorkshire, the soil it yields is usually thin, dry, and poor, furnishing crops of barley and turnips. Near Pontefract an important crop on the Magnesian Limestone is liquorice, which is used in making the well known confection, Pontefract Cakes.

The Triassic (Keuper) marls often yield calcareous clayey soils, which, although fertile, are stiff and not easy to drain.

The great economic importance of the Oolites and other limestones among the Jurassic strata tends to obscure the fact that the formation is, on the whole, a clay formation. The sandstones and limestones form the hills and escarpments that are conspicuous elements of the scenery of the "Jurassic" country (*Fig.* 179), but the clay "vales," especially the outcrops of the Lias clays, the Oxford Clay and the Kimmeridge Clay, occupy larger areas.

Among the Liassic rocks, the limestones yield loamy soils, and areas where they occur are often cultivated, contrasting with adjacent areas where clays and shales yield cold heavy soils given over to permanent pasture. The water thrown out from the overlying Lower Oolites often increases the wetness of the surface of the adjacent Lias clays, giving rise to patches of rushes, sedges, and similar water-plants, unless artificial drainage is resorted to. Root-crops and corn are grown in the warm coloured loamy soils yielded by the limestones of the Lower Lias in the south-western region of the outcrop, but although the alternation of clay or shale with limestone should produce a good soil, the clay is stiff and retentive of moisture, while the limestone beds tend to make ploughing difficult, with the result that a good deal of the outcrop supports grass land and pastures.

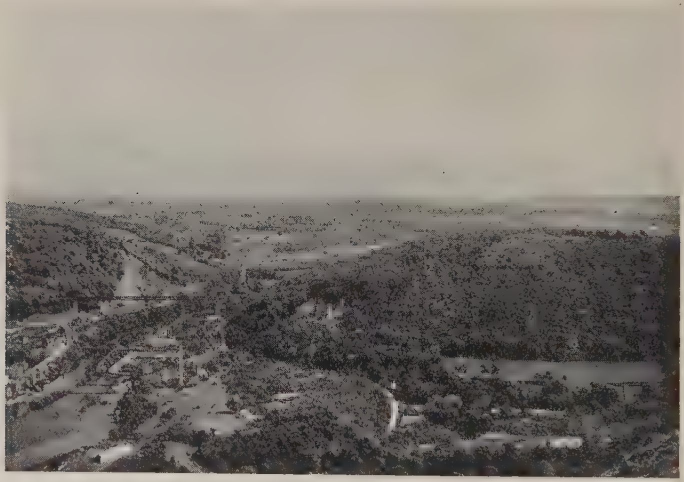

FIG. 195.—CARBONIFEROUS LIMESTONE HILLS NEAR CARDIFF, GLAMORGAN.

View from the Garth, Taff's Well, showing, in the middle distance, the Carboniferous Limestone hills of Little Garth and Fforest Fawr separated by the Walnut Tree Gorge, and beyond, the gently sloping coastal tract over which the Rivers Ely, Taff, and Rhymney make their way to the sea. (*Photo W.E.H.*)

An interesting example of the indirect effect of limestone upon agricultural pursuits is seen in certain parts of Somerset on the outcrop of the Lower Lias. The limestones have been extensively quarried, and owing to the fact that the strata lie almost horizontally the quarries were extensive but very shallow: disused quarries, partially filled in with limestone and shale debris—the waste material produced during the extraction of the useful stone —provided sheltered situations in which apples could thrive, and many old quarry sites are now flourishing orchards.

The " Marlstone " of the Middle Lias includes sandy, clayey and calcareous beds, and gives rise to a rich soil forming a strip of fertile cultivated land adjacent to the grazing land on the outcrop of the Lower Lias. In the midland region the ferruginous and calcareous beds of the Upper Lias yield reddish loams, often improved by the sand brought down by rain from the neighbouring hills where the Northampton Sands and similar rocks occur.

In many parts of its outcrop the Lias is so thickly covered by superficial deposits of various kinds, that the " solid " rock plays no direct part in determining the nature of the soil, but this applies also, of course, to the rocks of other formations, notably, as far as limestones are concerned, the Carboniferous Limestone, the Oolites, and the Chalk.

The limestones of the Oolitic Series usually yield a light and somewhat stony soil, and, as in the case of the Chalk, the tendency for water to pass underground causes the soil to be rather dry and liable to suffer from drought; see Additional Note, page 453.

The Inferior Oolite generally yields a " brashy " soil—that is, a somewhat stony loam upon which corn will grow and which is also suitable for certain root crops such as turnips. On the higher ground the soil is not usually deep enough for cultivation, and the somewhat barren land is given over to grazing. This was originally the condition on the Cotteswolds, but much of the district has now been brought under the plough (*Fig.* 196). The Great Oolite also gives rise to thin soils of similar character: they are seen, for example, in Gloucestershire (near Bath) and the adjacent part of Oxfordshire. In the more elevated regions, the soil, although good, is too shallow to be successfully cultivated. The Cornbrash, especially in the south-west, is, as its name implies, a rock that yields a good corn-growing brashy soil, and its outcrop is marked by a line of villages that have arisen, partly because of the fertile soil to which the rock gives rise, and partly because it yields an abundance of water.

The Corallian rocks are, as we have seen, very variable—both in a vertical sense as well as laterally—and the soils they yield are, accordingly, also variable. In Yorkshire a light sandy soil overlies the Calcareous Grit and often gives rise to moorland, while some of the other Jurassic limestones of the county—those to the west of Scarborough, for example—yield stony loams well suited to corn growing.

The bold hills where the Portland beds are typically developed are for the most part sheep-walks.

In sharp contrast to the calcareous and sandy divisions, the clay divisions of the Jurassic, where free from drift, usually give rise to heavy damp soils; this is especially the case with the Oxford Clay, and to a lesser extent applies also to the Kimmeridge Clay. Yielding readily to denudation, as clays usually do, they occupy low ground, and this, together with their impervious nature, often makes drainage difficult, but some of the best permanent pasture and dairying country occurs in the broad clay vales between the Jurassic limestone hills.

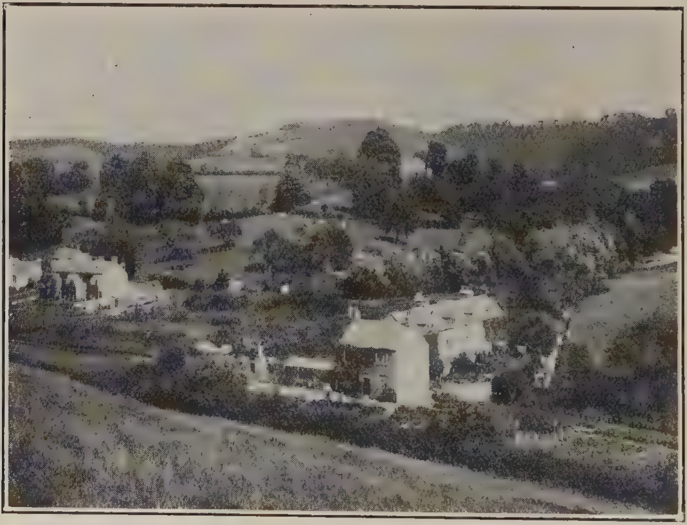

FIG. 196.—The Slad Valley, near Stroud.
Scenery of the "Oolite" country of the Cotteswold Hills.
(*Photo Frith and Co., Ltd.*)

An interesting example of the conditions, previously mentioned, arising where the soils have been derived from rocks of various kinds, is seen in Northamptonshire, where fertile country occurs around Kettering, because denudation has resulted in the development of a very complicated relationship between the outcrop of the Lias (mainly clays) and that of the Oolites (largely calcareous).

Limestones are so rare among the Lower Cretaceous strata that their influence in agriculture is negligible, but, although usually a tenacious impervious clay, giving rise to marshy land or oak woods, some parts of the Gault, especially in the middle of its outcrop, are calcareous marls yielding fertile soils.

The Chalk, as we have seen, varies greatly in the proportion of argillaceous material it contains, and the soils yielded by it are also variable. When the calcareous material of the pure varieties has been removed in solution, little remains to form soil at all, but the less pure varieties, especially among the Middle and Lower divisions, usually yield loamy soils, which, where cultivated, as in Hertfordshire and Cambridgeshire, are often devoted to turnip growing. The soil from the Chalk Marl, especially near its junction with the Upper Greensand Series, produces good soil for root crops and cereals, and where the Chalk supports timber, the beech is the characteristic tree; this is also the case with other limestones, as for example, the Inferior Oolites of the Cotteswolds. Yews and box are also prevalent on the Chalk.

Typical Chalk landscape is seen to advantage where neither glacial deposits nor extensive superficial weathering products are present on the Upper Chalk; this is the case over much of the South Downs and Salisbury Plain, where the higher regions are open pasture and the lower ground is arable, and the effects upon the soil (and therefore upon the agricultural conditions) of a covering of drift are well exemplified if such regions are compared with the Chalk areas of East Anglia and Lincolnshire, which are heavily drift-covered and largely arable.

The rolling chalk downs are specially suitable for sheep farming, and have long been utilised for that purposes, indeed, these districts have probably undergone less change since the first appearance of man than any other part of the country. With its short, springy, well-drained turf, the chalk country was early recognised as providing ideal conditions for horse trials, and as William Smith naïvely remarked in his "*Strata Identified by Organised Remains*" (1816) :—

> "The short turf on the Chalk Hills, the site of ancient British sports, the seats of Druidism and ancient Kings, will ever continue to be favourite places of amusement : Gentlemen of the Turf having found this to be the best for ascertaining the comparative speed of British horses, the races of Newmarket, Epsom, Salisbury, Brighton, and several other places being on the stratum."

The comparative "dryness" of the Chalk, owing to the tendency for water to soak in, has already been mentioned, but, owing to the smallness of the pores in the rock, water tends to move in it as a result of capillary action—that is, the tendency of a liquid to move through narrow fissures apparently against the law of gravity, owing to the existence of tension in its surface layers.* This has an important bearing upon the supply of moisture to plants growing in soils resting directly upon the chalk, because in dry weather there is a slow but steady rise of water even although the level at which the chalk is saturated may be scores of feet beneath the surface; in strong contrast is the case of the Thames Valley gravel (consisting of coarse grained material with relatively large pore spaces) where it was found that, even with the saturated zone only 16 or 20 feet beneath the surface, there was no marked tendency for water to rise into the soil [18].

None of the limestones in this country, more recent than the chalk, covers sufficiently large areas to need comment in connection with agriculture; where they do occur their behaviour is that normal to limestone. The loose shelly Crag deposits of Pliocene age were at one time dug for "marling" purposes, but the soils derived directly from the Crag are apt to be very loose on account of the incoherent sandy nature of the strata; in summer they tend to become dry and friable and may be blown about by the wind, like sand-dune material; a large part of the Pliocene outcrop is, however, concealed beneath a covering of glacial debris.

Lime in agriculture.—In addition to its influence by reason of the soils to which it gives rise, limestone is of interest to the agriculturist on account of the means it affords of supplying a soil-ingredient that is necessary to successful cultivation.

Owing to the complex nature of the reactions concerned in the breaking down of minerals during the process of rock weathering, various salts of calcium (such as the sulphate and the carbonate) may be present in the soil, but usually only the latter is meant when we speak of the lime-content of a soil.

As a rule, soils produced by the disintegration of rocks contain calcium carbonate as an original constituent, but if the rock itself contains but little of that substance only a small proportion will be present in the soil, and successful cultivation demands the addition of "lime" to make up the deficiency. It should be noted that even soils derived from the decomposition of limestone may be so deficient in calcareous material as to need " liming " : this is the case, as we have already seen, with the thin soils that represent the insoluble residue of the chalk.

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* An illustration of capillary action or capillarity is seen if a glass tube of very narrow bore, open at each end, is stood upright with its lower end immersed in water; the water will be found to rise in the tube to a height that depends upon the diameter of its bore; another instance is the "soaking up" of tea by a lump of sugar only partially immersed in that liquid.

The proportion of lime present in soil varies, therefore, from place to place, according to the material from which it has been derived, and from time to time, according to the extent to which the " lime " removed by growing plants is replaced by natural or by artificial means.

The removal of lime from the soil by solution in rainwater and by plants is much greater than appears at first sight : it has been calculated that on uncultivated ground the loss is, on an average, 7 cwts. per acre per annum, and in the case of dairy farms each cow takes at least 1¼ cwts. of lime from an acre of land per year to form milk : if the calves are reared, the lime of their skeletons also comes from the soil [23].

One of the principal functions of calcium carbonate (or of " lime ") in the soil, is to keep it in a neutral condition. The decomposition of organic matter produces material of an acid character, and this, if allowed to accumulate, will, in time, render the soil " acid " or " sour," and consequently infertile.

An alkaline condition is also unfavourable to plant growth, and in the case of a clay soil would alter its physical condition in such a way as to reduce its fertility. Calcium carbonate on the other hand, although capable of uniting with acids, is practically insoluble in ordinary water, and is to all intents and purposes neutral : it dissolves slowly in carbonated water, and combines with the acids in the soil ; the carbon dioxide set free during the chemical change, although of an acid character, is so feebly acid as to be harmless to plant life in the quantities in which it is generated within the soil. The nature of the chemical change in which the calcium carbonate is involved is indicated in the following equation :—

$CaCO_3 + H_2CO_3 \rightarrow Ca/$

$$CaCO_3 + 2HNO_3 \Longleftrightarrow Ca(NO_3)_2 + H_2O + CO_2.$$

$CaCO_3$	$2HNO_3$	$Ca(NO_3)_2$	H_2O	CO_2
Calcium carbonate	Nitric acid, produced as a result of the oxidation of nitrogenous material in the soil	Calcium nitrate	Water	Carbon dioxide, which unites with water, forming carbonic acid

Owing to its neutral character and its relative insolubility, calcium carbonate, greatly in excess of actual requirements, can be present in soil without harm, and such an excess serves to maintain a suitably neutral condition.

Another of the beneficial effects of the presence of calcium carbonate in the soil is that it promotes oxidation of the organic material, for if putrefaction rather than oxidation takes place the products are harmful and poisonous to plant life; lime also assists in making available the potash content of a soil, it improves the responsiveness of soil to treatment by phosphates, and is necessary for the growth of nitrifying bacteria, that is to say, of bacteria which, as a result of their own development, form nitrates that are essential to plant growth. Certain harmful organisms, such as a slime-fungus causing disease among turnips and swedes, cannot grow in the presence of calcium carbonate [24]; see Additional Note, page 453.

Part of the value of lime in soil treatment lies in its physical effect upon clay. Clay consists of very small particles—many of them less than 1/5000th of an inch in diameter—and since water spreads through a rock as a film upon the surfaces of the component particles, and the smaller the particles the larger their total surface area in a unit mass of rock, clay can absorb much more water than a coarser rock like sand. Indeed, unless adequately drained, clay soon becomes waterlogged, and since such a condition prevents the access of air, the soil will be barren and infertile. When wet, clay is sticky and hard to work, and during drought it loses so much water that it shrinks, and the cracks that develop tend to damage plant roots as well as to militate against the rise of water from the sub-soil by capillary action, in the manner already described.

It is found that lime causes the finest clay particles to coagulate and form larger particles, thus giving rise to a coarser texture, with its consequent advantages in the direction of a lighter, more easily drained, better aerated, and more easily worked soil. Lime, however, only effects very small particles, and cannot lead to the mechanical improvement of soils consisting of large particles.

The effects of lime upon soil are, therefore, very complicated—it is a plant food, and it influences both chemical and physical properties of the soil—and, naturally, its results will vary according to local circumstances: the best results can only be expected when it is applied in accordance with the needs of the soil as indicated by suitable chemical and mechanical analyses. A full discussion of these important matters, which involve some of the fundamental principles of agriculture, is beyond the scope of a work intended for the general reader, and for further information reference should be made to the standard works dealing with soil and its treatment [17, 17a]. The only other matter that need be mentioned in this connection relates to the method of supplying lime to soil in which it is deficient. The essential feature is that the calcium carbonate must be in a condition to fulfil readily the function for which it is applied. In addition, therefore, to being thoroughly incorporated with the soil it should be in a very fine state of sub-division in order to facilitate its solution, and on this account it is generally applied in the form of "slaked" lime.

Lime, in the strict sense of the word, is calcium oxide, and it is produced by heating limestone sufficiently to drive off carbon dioxide; the resulting product is "quicklime" (calcium oxide), represented by the formula, CaO.

If quicklime is allowed to absorb moisture from the air, it is converted into calcium hydrate, as indicated in the equation below, and in doing so it falls into a fine dry powder.

$$\underset{\text{quick-lime}}{CaO} + \underset{\text{water}}{H_2O} \Longleftrightarrow \underset{\text{calcium hydrate or slaked lime}}{Ca(OH)_2}$$

Further exposure results in the taking up of carbon dioxide, which gas is always present in the atmosphere :—

$$\underset{\text{slaked lime}}{Ca(OH)_2} + \underset{\text{carbon dioxide}}{CO_2} \Longleftrightarrow \underset{\text{calcium carbonate}}{CaCO_3} + \underset{\text{water}}{H_2O}$$

and calcium carbonate is once again produced. It is this substance that is needed in the soil, and the principal reason for converting it into lime instead of applying it direct, is to bring it into a suitable mechanical and chemically active condition. Ground quicklime is sometimes used, because it is believed to be more vigorous in its action.

It has been found, in most cases, that small applications of lime are proportionately more efficient than heavy ones. "It is to be observed," wrote J. A. Slipher, as a result of experiments made on various soils and with varying amounts of lime, "that the lightest rate of liming has effected the greatest proportionate change in soil reaction." In general, it is found that the application of from 1 to 2 tons of lime per acre every 4 or 5 years to a soil not naturally rich in lime yields good results.

It may be asked: if the lime applied to the land eventually reforms calcium carbonate, why should not the intermediate stages be eliminated, and ground limestone be used in its place? The precise nature of the difference between them is not fully understood, but it is certain that although alike in chemical composition, limestone and slaked lime that has become recarbonated differ in their physical properties and in the degree of their chemical activity. The neutralisation of the weak acids of the soil is much more readily accomplished by slaked lime that is being converted into calcium carbonate than by natural limestone, however finely it may be ground [20].

It is often considered that magnesian limestones are not satisfactory for making agricultural lime, but upon this matter there are differences of opinion: in some cases, lime made from dolomitic limestone has been used to advantage, as for example, in the tobacco-growing districts of North Carolina, where it showed a tendency to counteract the ravages of the plant disease known as Chlorosis [21]. It is interesting, in this connection, to recall the fact that magnesium is an essential constituent of *chlorophyll*—the green colouring matter of plants that is connected with the conversion of the light energy received from the sun into the chemical energy by which plants build up their tissues from carbon dioxide and water. From this it would follow that a deficiency of magnesium in the soil might be expected to reduce the activity of chlorophyll, and in that way to interfere with the development of plants [28].

In addition to its direct application to the land, lime is also used in making insect-killing mixtures, sheep-dips, Paris green, arsenical washes, Bordeaux mixture and artificial fertilisers, and other materials used by the agriculturist. (Bordeaux mixture contains copper sulphate and slaked lime, and Paris green is a bright green powder, used both as a pigment and as an insecticide, containing copper and arsenic.)

Not only is lime used in agriculture, but some limestones and other highly calcareous rocks have been applied direct to the land for a similar purpose.

The Chalk was at one time extensively used for "liming," especially in those parts of the Chalk outcrop where there was a superficial covering of poor clayey soil. The method of obtaining the chalk was by means of bell-pits similar to those to be described in connection with the Purbeck Limestone of Sussex. In parts of Buckinghamshire and Hertfordshire the pits often reached a depth of 50 feet, and penetrated right through the Upper Chalk to the level of the hard Chalk Rock beneath.

During the course of Geological Survey work in Buckinghamshire Dr. R. L. Sherlock [1] found the average number of bell-pits and old chalk quarries to be between six and seven per square mile: they are, of course, now represented by shallow depressions in the surface of the fields, for the bell-pits have collapsed and the shallow open pits have become overgrown. The general practice was to take from each bell-pit enough chalk to " marl " a field, and then partially to fill the hole by shovelling in such debris as was available. Sometimes the mouth of the shaft was blocked with timber and covered with soil; the decay of the former had been known to lead to the collapse of the latter and cattle have been lost in consequence. Even if no sudden collapse occurs, the gradual settling of the material gives rise to shallow depressions in the fields, some of which represent the sites of bell-pits while others are overgrown open-pits: their abundance in certain districts illustrates the extent to which " liming " by chalk was practised; a bell pit is depicted in *Fig.* 218.

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CHAPTER XIV.

LIMESTONE, WATER SUPPLY, ORE DEPOSITS, AND OIL.

> "Through crevices and cracks, here, there, and everywhere, the percolating waters find their way. Now some crevice is enlarged into a passage, now some weak joint in the passage becomes a chamber; and on the water rushes, steadily joining forces and accumulating until . . . it finds an outlet and rushes forth a considerable stream."
>
> H. E. Balch, in "*The Nether World of the Mendips.*"

Owing to the porous, jointed, and soluble character of the rock, areas of limestone do not lend themselves to the construction of surface reservoirs for the storage of water, and the importance of limestone in matters connected with water-supply lies in the readiness with which water passes into or through the rock, to supply springs or wells.

Records show that, in a recent year, of 285 million gallons of water supplied daily for domestic use from publicly owned springs or wells in this country, 163 million gallons—about four-sevenths of the whole—came from limestones, principally the Chalk, and if the amount from privately owned wells could be ascertained, the relative importance of limestone would be greatly increased [1].

The three great limestone series of this country—the Carboniferous Limestone, the Jurassic Limestones, and the Chalk—are each important water-bearing formations, but the conditions of storage differ as much as do the rocks themselves, and before proceeding to a brief discussion of the relation between limestone and water-supply in this country, it is desirable to describe in a general way the conditions under which water is stored in, and passes through, rocks.

General conditions governing the supply of water to springs and wells.—Of the rain water that falls on the surface of the earth, some evaporates, some makes its way into brooks or rivers and may eventually reach the sea, while the remainder (on an average about a quarter of the whole) soaks into the ground.

The extent to which it will soak in depends, of course, upon the permeability of the rock and upon the existence of cavities through which water may pass. To what depth the water can penetrate is not known; there is certainly a downward limit, because under the great pressures that exist very deep beneath the surface, no pores capable of conveying water can exist, but, at some depth beneath the surface there is a zone in which rocks that are not absolutely impermeable to water are always saturated; the upper limit of this zone is known as the " water-table " (*Fig.* 197), and above it the rocks are not saturated. In some places the upper limit of the saturated zone is above ground-level, and swamps or marshes occur, but in other places, although the continued addition of fresh supplies from the surface tends to cause the level of saturation to rise, it usually fails to reach ground-level because of the local occurrences of springs that cause the water to drain away, and thus keep the water-table at a depth that varies according to the ratio between the supply and the issue from the springs: in very wet weather the level of the water-table tends to rise, and in very dry weather to fall.

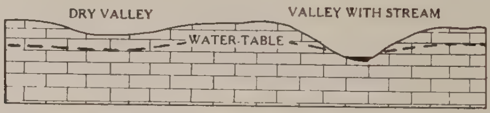

FIG. 197.—DIAGRAM ILLUSTRATING THE RELATION BETWEEN UNDERGROUND WATER, DRY VALLEYS, AND VALLEYS WITH STREAMS.

The diagram illustrates the conditions in a thick permeable formation such as the Chalk. The water-table is the upper limit of the zone of the earth's crust that is saturated with water.

The capacity of a rock for absorbing or transmitting water depends upon two principal factors, namely, its porosity and the extent to which it is affected by joints or other fissures (*Fig.* 198). Some rocks are permeable to water because the spaces between the particles are comparatively large, and others, although so compact as to be practically impermeable, may be strongly jointed or have well developed bedding planes and thus permit the passage of water. A rock that is neither porous nor openly fissured is practically impervious to water. It is the size of the pores, rather than the total amount of the pore-space that determines the facility with which a rock will absorb water and give it up again, for, as we have already seen, clay has a relatively large total pore-space, but the individual pores are so small that water passes very slowly through the rock, and in its relation to water-supply, clay may be regarded as a typical example of an impermeable material.

Underground water tends to accumulate in the porous and permeable strata (such as sandstones and porous limestones or well-jointed massive limestones and igneous rocks) and as such rocks are usually inter-stratified or associated with others that are impervious (such as clay, shale, and unjointed limestones and igneous rocks), the movement of underground water is subject to definite laws, and its behaviour can be foretold with considerable precision.

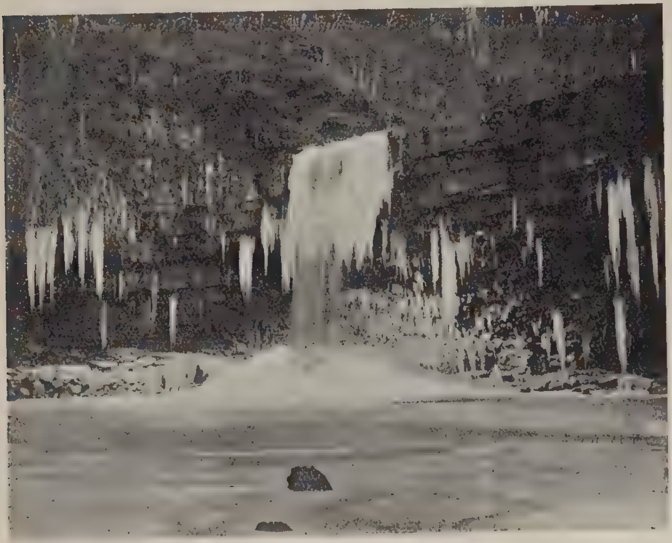

FIG. 198.—A FROZEN WATERFALL IN SOUTH WALES.

Ysgwd Gwladys, River Perddyn, Brecknockshire: the distribution of the icicles demonstrates the influence of joints and bedding planes in controlling the movement of water through rocks. (*Photo I.V.E.*)

Where a water-bearing rock rests upon impermeable strata, as in *Fig.* 199, there will be a tendency for water to accumulate in it, providing a supply that may be tapped by wells, and for springs to be thrown out along the junction between the two rocks. If, in addition to impermeable strata beneath, impermeable rocks occur above the water-bearing formation, the spaces that exist in the permeable rock constitute a buried reservoir in which water can accumulate free from contamination, for it is found that the deleterious substances and organisms present in surface waters do not penetrate with the water for any considerable distance unless there are well defined channels for its passage.

In cases where the rocks occur in a synclinal fold, or where faults bring permeable rocks against impermeable material and the water cannot escape easily, it will accumulate under pressure, and if the " head " is sufficient—that is, if the outcrop of the bed, where it receives its supply of water, is well above the buried portion of the stratum where the storage has taken place—water may rise in a well and may even flow from it without recourse to pumping; such is a true " artesian well " (*Fig.* 200). Many other factors are concerned in the supply of water from springs and wells, but the foregoing instances of simple cases are sufficient to illustrate the general principles, and to render intelligible a discussion of the water-bearing relationships of the limestones of this country.

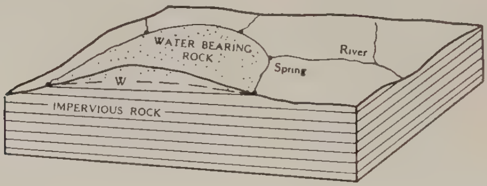

FIG. 199.—Diagram illustrating the formation of springs.

This imaginary block of the earth's crust illustrates one of the many ways in which springs arise. Water falling on the surface of the pervious stratum accumulates within it, but tends to drain away at its edges where impervious strata form the surface of the land. W = the water-table, and springs will be thrown out at the junction of the two rocks, as at " Spring."

Limestones as water-bearing rocks.—Springs occur in connection with the limestones (such as the Bala, Woolhope, Wenlock and Aymestry Limestones) among the Ordovician and Silurian strata, and with the Devonian Limestone of Devonshire, but the outcrops are all comparatively small, and the limestones older than the Carboniferous cannot be regarded as important water-bearing strata.

The Carboniferous Limestone, although the rock is usually so compact as to be almost impervious, is an important water-bearing formation, because, owing to the tendency for its fissures (such as joints and bedding planes, which are well developed and numerous) to be widened on account of the solubility of the rock in carbonated water, it allows water to pass underground with great freedom (*Figs.* 201-2). The water tends to follow fissures and to collect in caverns that may sometimes constitute reservoirs of considerable size (*Fig.* 202), and wherever conditions are favourable, springs will arise—as, for instance, near the junction of the main limestone with the argillaceous Lower Limestone Shales or other impervious strata, and wells sunk into the rock yield much water if they encounter a water-carrying fissure. The

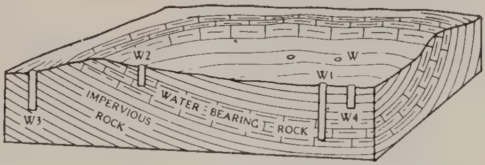

FIG. 200.—DIAGRAM ILLUSTRATING ARTESIAN WELLS.

An imaginary block of the earth's crust illustrating one of the ways in which water accumulates under conditions favourable to the supply of artesian wells. Water falls on the outcrop of the pervious strata, passes underground, and is imprisoned in those strata by the impervious rocks above and below them, giving rise to an "artesian basin." Wells sunk in the area underlain by the water-bearing formation will yield water when the permeable strata are reached, and if the site of the well (W1) is sufficiently below the level of the outcrop to provide the necessary "head," the water from the well may rise to the surface; nearer to the outcrop (W2) it would probably be necessary to pump the water to the surface, while wells (W3) sunk into the rocks below the permeable bed, or wells (W4) failing to reach it, would, of course, yield no water.

available supplies are, however, not very largely used, becaus the joints that allow the ready passage of water are also likel sources of pollution.

"Hard" and "Soft" Waters. — The water yielded by th Carboniferous Limestone, and indeed by any other limestone, i usually very "hard," on account of the opportunities it has ha of taking up calcium carbonate and other mineral salts. Fo example, it has been calculated that each million gallons of wate in the chalk carries one and a quarter tons of calcium carbonat

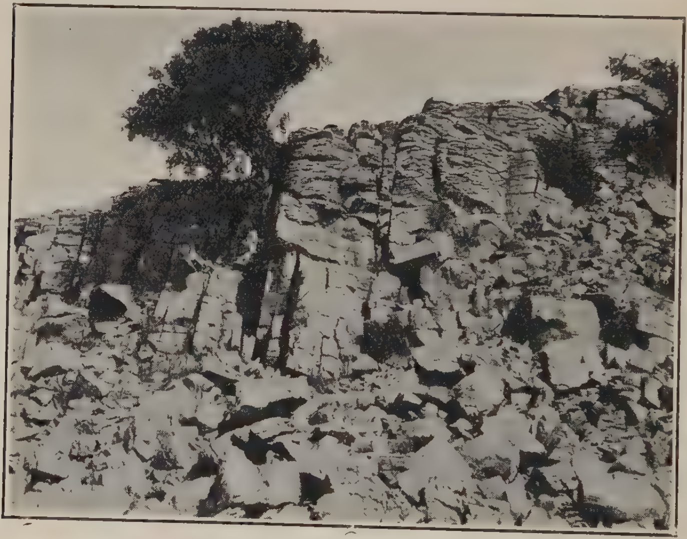

FIG. 201.—SCREES AND A LIMESTONE ESCARPMENT.

The Carboniferous Limestone near Ystradfellte, Brecknockshire, showing the way in which the joints and bedding planes (near top of cliff) have been widened by percolating water.

in solution, while in the water annually pumped from that rock in this country, nearly 64,000 tons of chalk are removed [1].

In the case of limestone water the hardness is mostly due to the presence of the bicarbonates of calcium and magnesium, but on boiling, the carbon dioxide (by reason of which the mineral matter is held in solution) is evolved, resulting in the formation of the normal carbonates which are practically insoluble and are, in consequence, precipitated. On this account the hardness due to the dissolved carbonates is known as "temporary," to distin-

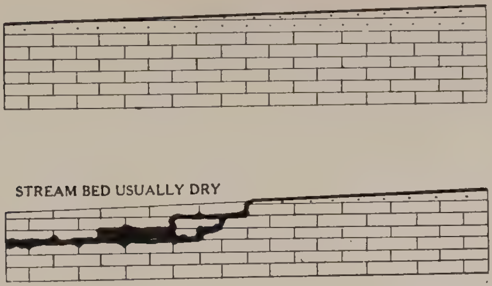

FIG. 202. — DIAGRAM ILLUSTRATING THE UNDERGROUND PASSAGE OF WATER IN A LIMESTONE DISTRICT.

The upper diagram represents a section along a river bed in a district where the rocks are not soluble in water, and the lower diagram represents the conditions frequently found where a river flows partly over limestone, and dissolves channels along planes of jointing and bedding.

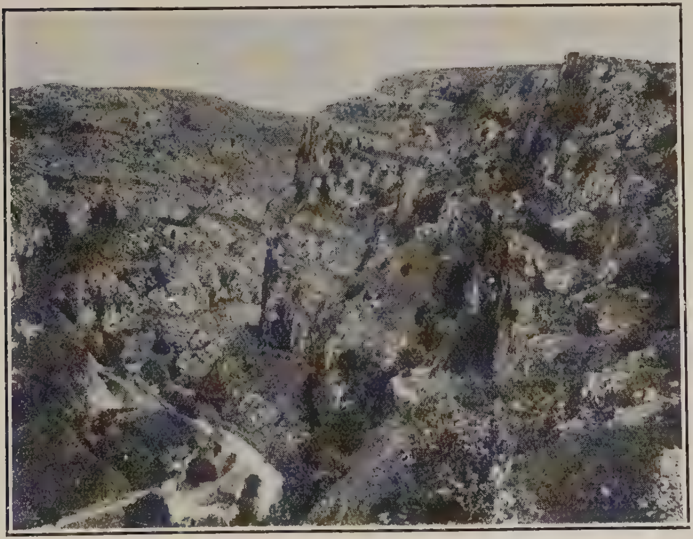

FIG. 203.—CHEDDAR GORGE, SOMERSET.

A deep streamless gorge in a limestone (Carboniferous Limestone) country: the water moves along in underground channels. (*Photo Frith and Co.*)

guish it from the hardness that is not removed by boiling—" permanent hardness," due mostly to the presence of calcium sulphate.

It is the deposition of calcium carbonate that gives rise to the " fur " that encrusts vessels in which hard water is boiled. The change is represented by the following formula :—

$$\underset{\substack{\text{Calcium bicarbonate}\\ \text{(soluble)}}}{Ca(HCO_3)_2} \Longleftrightarrow \underset{\substack{\text{Calcium carbonate}\\ \text{(insoluble)}}}{CaCO_3} + \underset{\substack{\text{Carbon}\\ \text{dioxide}}}{CO_2} + \underset{\text{Water}}{H_2O}$$

Many limestone waters are too hard to be satisfactorily used in industry or for domestic consumption ; for example, boilers may become very quickly lined with " scale " that lowers their efficiency and may even constitute a source of considerable danger; pipes conveying hard water tend to become choked by deposits such as those alluded to in connection with stalagmite and tufa, while for household use, one of the objections to hard water is the difficulty with which such waters combine with soap to form a lather.

The objection to hard " limestone " water for boiler use arises from the facts that the " scale " not only conducts heat badly and therefore retards the passage of heat into the water and involves waste of fuel, but, if the water-level in the boiler gets low, the scale is liable to separate from the metal, because the rates of expansion of the two substances are different. If, under such conditions, cold water enters the boiler, it may result in the cracking of the " scale," allowing the water to touch the overheated metal, producing a sudden rush of steam which might, under certain circumstances, cause an explosion.

The difficulty of making a lather with hard water arises from the fact that soap, which is a fatty acid, is decomposed by calcareous salts, yielding an insoluble curdy precipitate. The formation of the insoluble material continues as long as any calcium (or magnesium) salts are present in the water, after which the soap is able to produce a lather. Hard water, therefore, involves waste of soap, in addition to the disadvantages arising from the abundance of " scum."

The reaction between calcareous salts and soap is made use of in determining the hardness of water and in comparing the hardness of one water with that of another. The hardness is determined by means of tests made with soap solution of a known strength, and it is expressed in degrees, each degree indicating the presence of one grain of calcium carbonate (or of any other salts of calcium and magnesium) per gallon of water [2, 5].

Various processes are adopted to soften waters that are excessively hard, but their discussion is beyond the scope of this work, and reference to one or two well-known methods will illustrate the principles involved : one process, known as " Clark's process " after its inventor, Dr. Thomas Clark, who, in the middle of last century was Professor of Chemistry at Aberdeen, appears at first sight to be paradoxical, because it aims at the *removal* of hardness due to calcium carbonate by the *addition* of lime. Water containing quicklime, partly in solution and partly in suspension (milk of lime), is mixed with the hard water in suitable proportions, previously calculated according to the extent of the hardness to be removed, and the following reaction takes place :—

$$\underset{\substack{\text{Calcium bicarbonate}\\ \text{(soluble)}}}{Ca(HCO_3)_2} + \underset{\text{Lime}}{CaO} \Longleftrightarrow \underset{\substack{\text{Calcium carbonate}\\ \text{(insoluble)}}}{2CaCO_3} + \underset{\text{Water}}{H_2O}$$

The lime combines with some of the carbon dioxide in the soluble calcium bicarbonate, thus forming normal calcium carbonate and converting the bicarbonate also into the normal carbonate; the latter, being practically insoluble, is thrown down in the solid state and the softened water can be decanted off. Not only does the process render the water " soft," but the precipitates assist in the removal of organic matter, and the finely divided calcium carbonate so produced is a saleable commodity.

Modifications of Clark's process, and others of somewhat different character, have been introduced in order to eliminate some of the " permanent hardness " of water [4-6]. Of the industrial processes some aim at softening the water before use and others treat it within the boiler itself.

An interesting process was introduced in 1907 by Professor Ganz of Berlin : it employs certain complex silicates made by fusing quartz-sand, china-clay, and soda-ash (that is, crude sodium carbonate containing small amounts of sodium sulphate and sodium chloride, produced at one stage in the making of pure sodium carbonate); when sodium is the essential " base " these complex silicates are soluble, but they react with salts of calcium and magnesium producing insoluble precipitates. On account of the readiness with which the change takes place the process is known as the permutit process, from the Latin *permutare,* to exchange. Water softened by the permutit process loses both " temporary " and " permanent " hardness and contains no soap-destroying or scale-producing ingredients.

Although relatively soft waters are necessary for boilers, laundries, dye-works, and for many other purposes, total absence of dissolved mineral salts is undesirable and a reasonable amount of " hardness " is necessary in industrial and domestic waters. Very soft waters are more liable than hard ones to take up organic contamination, to dissolve the lead from new pipes and cisterns, and to corrode iron pipes and boilers. Cases of lead poisoning have been traced to the solvent action of soft water upon lead [7], but after a time carbonate of lead tends to form on the surface of the metal, and as that substance is insoluble the danger soon disappears. Water yielded by the Magnesian Limestone in Durham is considered good for brewing purposes, and at Burton, water with permanent hardness, due to calcium sulphate, is used in making pale and bitter ales.

Limestones as water-bearing rocks (*continued*).—Returning to our consideration of the limestones of this country in relation to water, we find that the limestones of the Lower Lias are water-bearing, especially near the outcrop where the beds are more affected by open joints and fissures. Many domestic wells derive their supplies from this source; but, it will be remembered, the Formation often consists of thin beds of limestone alternating with shales, and since the shales naturally interfere with the downward movement of the water, most of the supply is from shallow wells, and, in consequence, the supply is never great and contamination is often experienced.

The Middle Lias Limestones yield water in Rutland and Northants, but it is often, like the rocks from which it issues, ferruginous.

The Inferior Oolite Limestone is one of the most important of the Jurassic water-bearing formations. Springs are thrown out near its junction with the clays of the Upper Lias, and there are copious springs in the neighbourhood of Bath, Stroud, Evesham and other places along the northern Cotteswolds. The Lincolnshire Limestone, especially in Lincolnshire, where it is over 80 feet thick and has the impervious Estuarine Series above and the impervious Upper Lias Clays below, yields much water to springs and wells; its outcrop is fairly free from drift and varies in width from 2 to 3 miles in the north to from 4 to 6 miles in the south. Many of the wells are true artesian wells, and from one at Bourne the water rose 40 feet above the surface of the ground. The Great Oolite also yields water over most of its outcrop.

The oolitic limestones are themselves often permeable to water, but the supplies to wells are, as in the case of the Carboniferous

Limestone, largely dependent upon fissures; much of the flow is along the bedding planes and the quantity available is naturally dependent upon the width of the outcrop, for where the rocks are gently inclined and large areas are exposed, more water can pass beneath the surface than will be the case if the outcrop is narrow, either because the bed is thin or its dip steep.

Supplies from the Forest Marble are variable because the division includes so many rock types: the porous limestones are permeable but the clays restrict the absorption of water and interfere with its underground movement; see Additional Note, p. 455.

The number of villages situated on or near the outcrop of the Cornbrash indicates its former importance as a source of water when comparatively small supplies were sufficient, but owing to the fissured and rubbly character of the rock and its inconsiderable thickness (average about 20 feet), the water is liable to contamination and often fails in dry seasons.

The Corallian Beds are an important source of water where they are represented by limestones and sandstones. In the south (Dorsetshire) the limestones are the most important water bearers, but in Bedfordshire and Cambridgeshire where the series is almost entirely argillaceous (the *Ampthill Clay*) it does not usually yield water except where local bands of limestone or other permeable rocks are met with; in Yorkshire, however, the Corallian beds again become important as water-bearers, for they include many calcareous divisions such as the Calcareous Grit and the Scarborough Limestone, and springs and wells are both abundant and productive.

The Portland Beds are water bearing, and springs are abundant in the Isle of Portland, but the natural drainage is such that wells are not usually successful. If near the coast, they are liable to contamination by sea water, especially if heavily pumped, and these factors, together with its comparatively limited outcrop cause the Portland Stone to rank low among limestones as a water-bearing rock. The same applies to the Purbeck limestones, which, in addition to having only small outcrops are much subdivided by clay beds, and except where the rock is more than usually fissured, water is neither abundant nor freely circulating.

Limestones are rare among the Lower Cretaceous strata, but the thin shelly limestones (*Paludina* marbles) in the Weald Clay provide small supplies of water for cottages, and the Kentish Rag, especially near Maidstone, also carries water near the surface where the rock is fissured, but it is, however, liable to contamination.

The Chalk is one of the most important water-bearing formations of this country, partly because of its wide extent, and partly on account of the convenient association of permeable and impermeable strata. As a rule, the Chalk readily absorbs water, but owing to the extremely small pore spaces, percolation when the rock is saturated is very slow; indeed, it has been estimated that in the case of some varieties of chalk, water takes more than 15 hours to pass through a foot of unfissured rock [8]. Therefore, as in the case of other limestones, the supply from wells depends to a large extent upon fissures, which are usually numerous; an illustration of the importance of fissures is afforded by two wells put down into the Chalk near Oxford Circus, London, in the same year (1907) and to practically the same depth; one yielded 3,500 gallons of water an hour, and the other, which passed through unfissured rock, practically none.

Although, as we have seen, there are considerable lithological differences between the various subdivisions of the chalk—the pure white Upper Chalk, and the argillaceous Lower Chalk and Middle Chalk—water appears to impregnate the formation as a whole, passing downwards until it reaches the Chalk Marl, which, being relatively impermeable, tends to hold it up. Thus, since water falling on the Chalk tends to soak in, rather than to run off (that is, of course, where no covering of Drift or " Clay-with-Flints " occurs), the formation may be regarded as an immense storage reservoir. It has been calculated that one square mile of Upper Chalk, a yard in thickness, contains nearly 3,500,000 gallons of water when " dry," and 200,000,000 gallons when saturated [9].

Springs are thrown out wherever conditions favourable to spring-formation occur—as for example, along the base of the Chalk escarpments, and at the junction of the Chalk and the Eocene strata, where the dip slopes of the former pass beneath the latter in the syncline of the London Basin.

The London Basin is an excellent example of an " artesian basin." The essential structure, as *Fig.* 38 indicates, is that of a synclinal fold; the trough-like fold of Chalk rests on a foundation of impervious material, and the rock is in part covered by impervious strata that prevent the access of water, except at the outcrop. As a rule the supply is drawn from the Upper Chalk, although many wells derive ample supplies from the lower divisions. At great depths in the heart of the syncline the pressure is such that fissures are less frequent and less open than they are where the rock approaches nearer to the surface, and the most productive wells are, therefore, situated near the borders of the outcrop, although many borings under London itself have yielded copious supplies. At the south-western extremity of the Cretaceous outcrop in Devonshire and South Dorsetshire, the Chalk and the Upper Greensand form an almost continuous water-bearing formation, because, in that district, there is no representative of the argillaceous Chalk Marl at the base of the Lower Chalk.

The Tertiary limestones are, as we have seen, too thin and too small in extent to constitute important water-bearing formations, but supplies for local use have been obtained from the Bembridge Limestone and the Headon Limestone in the Isle of Wight, and from some of the divisions of the (Pliocene) Crag. Springs are often thrown out where the porous Crag deposits rest upon the London Clay, and the water from the Red Crag, a deposit that owes its red colour to the presence of iron, is sometimes ferruginous.

Limestone and ore deposits; iron ores. — Closely connected with the movement of water through limestone and the solubility of the rock, is the occurrence in some limestone formations of valuable metallic ores. During its passage underground, water has opportunities of dissolving mineral salts that may be present in some of the rocks through which it moves, and when, on reaching a limestone, the water commences to dissolve that rock, it is often at the expense of the deposition of the metallic compounds. We find, therefore, that certain valuable ore masses represent material that has been deposited in place of limestone dissolved away by underground water.

For example, during the long period of uplift, rock-folding, and erosion that followed the formation of the Carboniferous deposits, the products of denudation were, to a large extent, spread over the country, and, as the marls, sands, and conglomerates of the Triassic formation rest sometimes upon the Coal Measures, and sometimes upon the Carboniferous Limestone, or upon still older rocks that had been laid bare by denudation; see *Fig.* 204.

Owing to the luxuriant plant life in the Coal Measure swamps and forests there was an abundance of decaying vegetation, the reducing action of which influenced the disposal of the iron set free during the decomposition of the rocks that were being denuded, and there was a tendency for iron compounds to be deposited with the sediments that were accumulating, instead of, as is more often the case, being carried away in solution in the waters of brooks and rivers. In consequence, there are, in the Coal Measures, vast quantities of "ironstone" — an impure clayey form of iron carbonate, sometimes present as nodules resembling in occurrence although not in composition the calcareous concretions of the London Clay and other clays, and sometimes occurring as well defined beds.

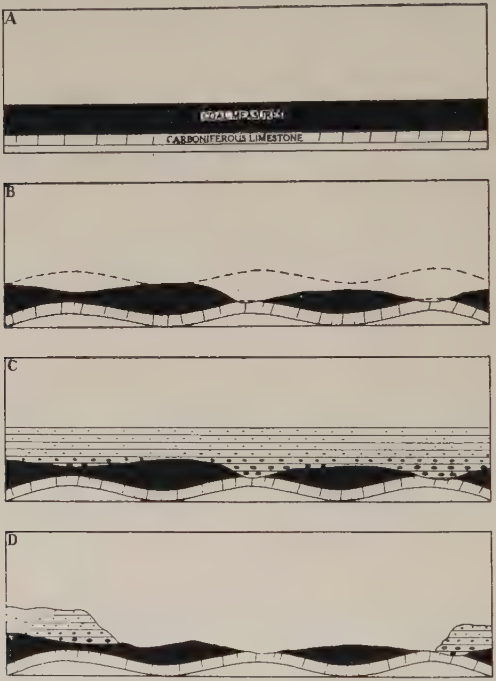

FIG. 204.—DIAGRAM ILLUSTRATING THE RELATION BETWEEN THE TRIASSIC ROCKS AND THOSE UPON WHICH THEY REST.

A, conditions after the deposition of the Carboniferous Limestone and the Coal Measures (including the Millstone Grit) as more or less horizontal, widely-spread strata; *B* and *C*, conditions after the Carboniferous rocks had been thrown into folds, in part denuded, and covered by newer strata; *D*, conditions at the present time—the covering of newer strata has been partly denuded away, giving rise to exposed coalfields (centre), and concealed coalfields (sides).

The downward percolation of iron-bearing waters from the Trias gave rise to deposits of iron ore in the Carboniferous Limestone; at the present time the Trias is still seen to rest on the limestone in some places, as on the right of Section *D*, but elsewhere, as in the centre of that section, it has been completely removed by erosion; but the occurrence of iron ores in the limestone is one of the proofs of the former wider extension of the Triassic rocks.

During Triassic times, arid and desert-like conditions often prevailed; these, too, were unfavourable to the removal of iron in solution, because streams tended to lose themselves in the surface deposits as they do in arid regions to-day, and few if any conveyed their water to the open sea. The iron, therefore, tended to remain, in an oxidised condition, in the Triassic deposits. Subsequently the iron compounds were taken into solution by percolating underground waters which, here and there, reached the Carboniferous Limestone below, and interactions between the calcareous rock and the ferruginous waters resulted in the limestone being locally replaced by iron oxide (hæmatite).

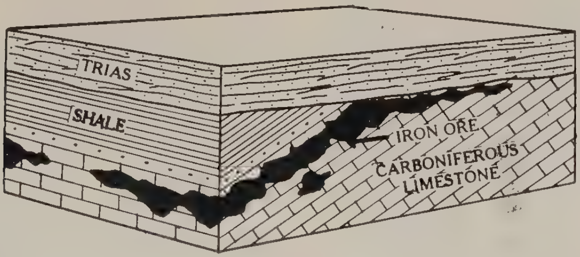

FIG. 205.—THE OCCURRENCE OF IRON ORES IN LIMESTONE.

Diagrammatic representation of the conditions under which iron ores occur in association with the Carboniferous Limestone south of Llantrisant in Glamorgan and also in other parts of the country. The ores resulted from the replacement of part of the limestone by ferruginous material carried down from the overlying Triassic deposits by percolating water, and the ore masses resemble, in shape and distribution, the solution caverns often seen in limestone masses.

Near Llantrisant in Glamorgan, for example, the Trias still remains, resting upon the Carboniferous Limestone, and the diagram in *Fig.* 205 illustrates the general relationship of the ore to the limestone. Most of the replacement took place in the topmost layers of the limestone; owing to the prevailing dip, however, the limestone passes beneath the shales of the Millstone Grit, and since these strata are impervious, the water continued to move along in the limestone beneath the shale covering, depositing its iron, and removing calcium carbonate. In some cases the iron ore masses are seen to be associated with faults that facilitated the access of the water to the limestone.

Iron ore deposits, generally similar in nature and origin to those described in the previous paragraph, occur in other parts of Glamorgan, in the Forest of Dean, in North Wales, Derbyshire, Durham, Cumberland, and Lancashire; many of them have been and some still are extensively mined [10-12]. The iron has apparently all been derived from superincumbent rocks; in some cases the latter still remain, but in other districts they have been removed by denudation from immediately above the ore bodies.

That the change has been due to water-action is indicated by the fact that the outlines of the ore bodies are in many cases strikingly like the limestone-caverns that are known to have been produced by solution (see *Fig.* 202): the nature of the ore and its relation to the limestone indicates, however, that the ore bodies do not usually represent *cavities* that have been filled with ore, but are actually replacements of the limestone. Further proof that this is the case is seen in the occurrence in the ore of fossil shells completely changed into hæmatite. A few miles north of Cardiff, for example, a thin bed of crinoidal limestone has been to a large extent replaced by hæmatite, and is now a dark red heavy ore, but the fossils are as clearly preserved as in the original rock [13]; *Fig.* 206.

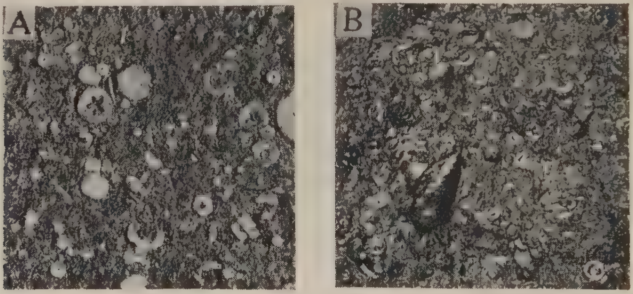

FIG. 206.—IRON ORES DERIVED FROM LIMESTONE.

Photographs (natural size) of (A) weathered surface of limestone containing fragments of crinoid skeletons, from the Carboniferous Limestone north of Cardiff, and (B) a specimen from the same group of rocks about half a mile away, in which the calcareous matter has been, to a large extent, replaced by oxide of iron, without destroying the identity of the fossils.

A matter of interest in South Wales and the Forest of Dean is that the hæmatite ores are definitely associated with highly dolomitised limestones; they occur in rocks that were originally ordinary calcareous limestones but that have undergone subsequent dolomitisation; this suggests that the formation of both ore and dolomite are connected with the permeability of the rock—a character that allowed iron-bearing and magnesium-bearing waters to gain access to the strata in which dolomite and hæmatite now occur [12].

Lead and zinc ores. — The known ferruginous character of the Trias and the fact that the iron ores tend to die out downwards, indicate that water percolating down from the surface was responsible for the change, but in the case of the lead and zinc ores that occur in some parts of the Carboniferous Limestone, the metallic compounds were probably brought up from the depths of the earth's crust [14].

In North Wales (Flintshire and Denbighshire) lead and zinc ores occur in the Carboniferous Limestone (as well as in other divisions of the local Carboniferous Series). The ores sometimes occur as material filling fissures associated with faults and joints, and sometimes in masses that follow the direction of the bedding; in the latter case they are, like the iron ore masses previously described, similar in shape and arrangement to cavities hollowed out by solution. The metallic minerals appear to have been of deep seated origin, and to have been brought up by ascending waters that moved along fissures due to faults, joints, or bedding planes. The fissured and cavernous Carboniferous Limestone (and also the permeable Cefn-y-Fedw Sandstone associated with it) provided a convenient situation for the interaction of mineral bearing waters and the deposition of ores [15]; see *Fig.* 207.

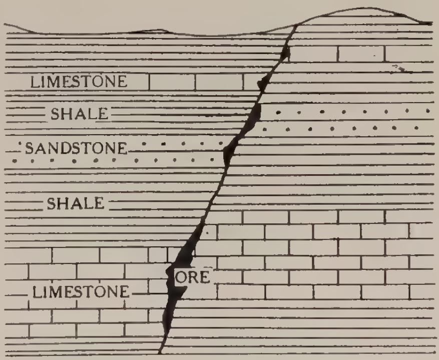

FIG. 207.—DIAGRAM ILLUSTRATING A MODE OF OCCURRENCE OF LEAD AND ZINC ORES.

The diagram is based upon sections prepared by the Geological Survey, and illustrates the manner in which ore has been deposited in fissures in the earth's crust. It is most abundant where the fissure crosses soluble rock like limestone, or porous rock like sandstone.

In North Wales, the lowest part of the Coal Measures is represented by the *Holywell Shales*; these are, naturally, much less pervious to water than the sandstone and limestone beneath, and they played an important part in the deposition of the ore, in that they prevented the further upward movement of the mineralised waters. The Holywell Shales are, moreover, highly charged with pyrites, and the sulphurous gases arising from the decomposition of that mineral probably interacted with the soluble salts of lead and zinc, giving rise to insoluble sulphides, such as zinc blende (zinc sulphide) and galena (lead sulphide). Bands of shale or shaly limestone in the main Limestone have also played a similar part in determining the deposition of ore, because it is often found that the ore bodies are most abundant and richest in the limestone beneath a covering of shale; *Fig.* 208.

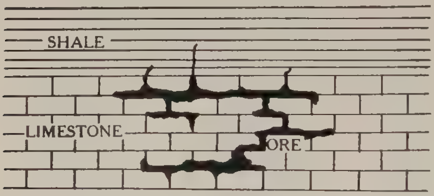

FIG. 208.—DIAGRAM ILLUSTRATING A MODE OF OCCURRENCE OF LEAD AND ZINC ORES.

The diagram is based upon sections prepared by the Geological Survey to illustrate certain occurrences of ore in North Wales. The ore bodies resemble in shape and occurrence the water-worn cavities frequently found in limestone masses, and an overlying bed of impervious shale has had the effect of preventing the further rise of the mineral-bearing waters.

Lead and zinc ores are found (also in the Carboniferous Limestone) in Derbyshire, Durham and Northumberland; the ore sometimes occurs as a filling to former cavities, but sometimes (in Weardale) it has *replaced* the rock, as in the case of the hæmatite ores [16]. In these districts also, the abundance of the ores in limestone is due to the solubility of the rock, by reason of which it can be replaced by ores, or can provide fissures in which they may be deposited.

Reference has already been made to the iron ores resulting from the partial replacement by iron of the calcium carbonate of oolitic limestones in the Oolitic and Liassic divisions of the Jurassic rocks [17].

Limestone and natural oil.—Although, as a result of laboratory experiments, it has often been claimed that natural "oil" has been produced in the interior of the earth by inorganic processes such as by the action of superheated steam upon compounds of iron and carbon, it is now generally admitted by most authorities that the substance is of organic origin. Upon the question as to whether it has resulted from the alteration of vegetable matter or of animal matter there is less uniformity of opinion. The fact that large quantities of oil are derived from strata (Ordovician and Silurian) formed at a time when plant life had not assumed the importance it acquired in later stages of the earth's history, favours an animal origin, although it is certainly the case that oil is often associated with coal and other extensive accumulations of the remains of ancient plants. Both vegetable and animal tissues are capable of giving rise to natural oils, but the contribution made by animal remains is probably much greater than at first appears to be the case.

A thick sedimentary deposit, accumulating fairly rapidly and enclosing an abundance of animal remains, would contain vast quantities of organic material, which, under suitable conditions, might be converted into mineral oil as a result of the changes induced by the heat and pressure that affect deposits buried beneath a considerable layer of superincumbent strata. It is not possible here to discuss the principles of the occurrence and exploitation of oil [see, however, 18-20], but reference has been made to the subject because of the association of oil with the Carboniferous Limestone in various parts of this country.

The principal conditions necessary for the occurrence of oil are (1) organic material, the alteration of which has yielded the oil, and (2) a porous or cavernous rock in which the oil has been able to accumulate, with (3) a covering of rock impervious to oil, the function of which is to limit the upward movement of the material. If, in addition, the strata occur as an anticlinal fold, or as a dome-shaped fold, the oil may accumulate under the arch or dome in commercially important quantities and even under pressure, like the water in a true artesian well.

The Carboniferous Limestone, in many districts, satisfies some of these conditions. It is a thick deposit, which, judging from the great abundance of its fossils, must have been extremely rich in organic matter. It is often succeeded by the sandstones and conglomerates of the Millstone Grit, but these, in turn, are normally covered by the thick and impervious shaly strata of the Millstone Grit and the Coal Measures.

Of the total world oil-production up to 1923, about 34 per cent. was derived from Carboniferous and Permian strata, and but for the extreme denudation which ensued after the close of

Coal Measure times—denudation that in many places cut deeply into the Carboniferous strata—it is likely that much oil would have been preserved in the rocks of that age that occur in various parts of this country.

As it is, small quantities of oil and bituminous compounds such as *elaterite* (mineral bitumen) and *hatchettine* (mineral wax) have been found in our Carboniferous rocks, and most of the domestic output has been derived from the argillaceous divisions of that system—oil shales sufficiently rich in hydrocarbons and bituminous matter to yield oil on distillation.

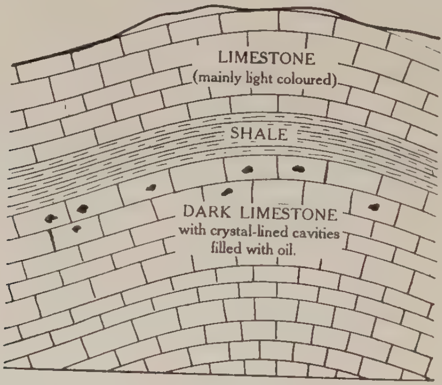

FIG. 209.—DIAGRAM ILLUSTRATING THE MODE OF OCCURRENCE OF MINERAL OIL IN THE CARBONIFEROUS LIMESTONE.

The diagram is based upon a large quarry section in Brecknockshire. The oil appears to have been associated with certain dark bituminous limestones, and has risen to the crest of an anticlinal fold; further upward movement was prevented by the beds of impervious shale.

Seepages, and in some cases appreciable flows of oil, had long been known to occur in Derbyshire and Staffordshire, and since the geological structure of the district was regarded as favourable to the occurrence of oil in commercial quantities in the upper beds of the Carboniferous Limestone or in the superincumbent Coal Measures, an exploration scheme was inaugurated in 1918 and several boreholes were put down, but although gas and oil were met with in most of them, the yield was insufficient to constitute a serious contribution to the country's natural resources.

The conditions under which oil may occur in the Carboniferous Limestone can be studied in various localities where beds of shale are associated with highly bituminous limestones. (The bituminous limestones are often dark in colour and usually emit a peculiar fetid odour when struck with a hammer.) For example, at Pontsticill, in Brecknockshire,* the face of an important quarry shows a band of shale in the form of a gentle anticlinal fold (*Fig.* 209), and in the limestone immediately beneath the shale some of the crystal-lined cavities such as commonly occur in limestone are found to be filled with a thick oily substance that runs away when the cavity is broken into, leaving a film of thick yellowish grease which rapidly darkens on exposure to the atmosphere. Except in being quite soft, the greasy interior lining recalls the mineral tallow (hatchettine) found in cavities in certain nodules of ironstone that occur in the coal bearing strata of various localities [21].

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* My attention was drawn to this interesting occurrence by Captain H. Morley Lewis, of Pontsticill.

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General references and local details relating to limestone and water supply will be found in the Memoirs of the Geological Survey devoted to Wells and Springs of several of the English counties: a full list of these Memoirs will be found in the latest of them—"The Wells and Springs of Gloucestershire" by L. Richardson, 1930.

CHAPTER XV.

LIMESTONE IN THE SERVICE OF MAN; CALCAREOUS BUILDING STONES.

> "A more intimate acquaintance with the writings of our predecessors . . . will lead us to a better appreciation of the successive phases through which science has passed . . . and will thus broaden our outlook. . . . We may find every here and there, germinal ideas which have remained unnoticed, but which may indicate fresh lines of enquiry to be pursued in the clearer light of modern research."
>
> SIR A. GEIKIE, *Presidential Address to the Geological Society* (1908).

In this and the following chapters it is proposed to review the industrial applications of limestone and to emphasise its importance as a national asset; the treatment will of necessity be brief, and, in accordance with the plan hitherto adopted, the discussion will be given an historial setting.

Limestone in prehistoric times.—Perhaps the earliest relation between man and limestone belongs to the time when our primitve forefathers took shelter or made permanent residences in caves that had been hollowed out of limestone by the action of percolating water, sometimes decorating the walls with paintings or drawings that amaze us by their vigour and artistic talent, as much as by their immense age [1].

The rock was, in general, too soft to be used in the manufacture of weapons or tools, although a knife-like implement found at Crambe in Yorkshire had been fashioned from shelly oolitic limestone, and axe-heads of similar material have also been discovered; while a carved "button" or circular ornament of fine-grained limestone was found in a Bronze-Age burial mound at Butterwick, also in Yorkshire [2].

The men of early Bronze-Age times frequently made use of limestone when erecting the chambered tombs (dolmens or cromlechau) of the period, remains of which still occur in various parts of the country. *Fig.* 210 illustrates the appearance of one of these ancient erections in its present condition, although originally many of them were buried partially or entirely beneath a mound of earth and stones. In some cases, as for example, in Anglesey, Carboniferous Limestone has been used in building cromlechau [3], but that illustrated in *Fig.* 210, which is near St. Lythans in Glamorgan, was built with an earthy porous limestone of Triassic age. Similar stone was used in another at St. Nicholas, also in Glamorgan. The capstone of this great tomb measures 23 feet by 15 feet and its maximum thickness is over 3 feet; it is supported on other stones of a similar kind arranged to enclose a roughly rectangular space between 5 and 6 feet high. A mound of earth, surrounded by a wall of limestone blocks, formerly covered the cromlech, and *Fig.* 211 shows a portion of one of the walls which must have been erected considerably more than 3,000 years ago [4].

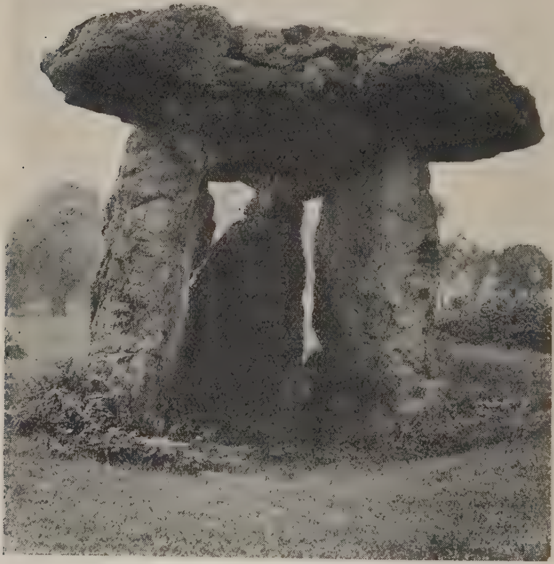

FIG. 210.—A PREHISTORIC LIMESTONE STRUCTURE.

A dolmen at St. Lythans in Glamorgan, built of tufaceous limestone of Triassic age; the height is about 10 feet.

Fig. 212 illustrates portion of the remains of an ancient British fortified village—Din Lligwy, near Dulas Bay, on the north-eastern shore of Anglesey. A series of circular beehive-shaped huts was enclosed by a rectangular wall and the stone used was Carboniferous Limestone from the immediate neighbourhood [3].

Some of the oldest known excavations in this country are the so-called Grimes Graves near Brandon in Essex, and certain pits at Cissbury in Sussex, made in the Chalk by early man in search of flint. At Brandon, well-like shafts were dug, from which galleries radiated not unlike those in the bell pits of later days (see *Fig.* 218). The excavation was accomplished by means of picks made from the antlers of red deer [2].

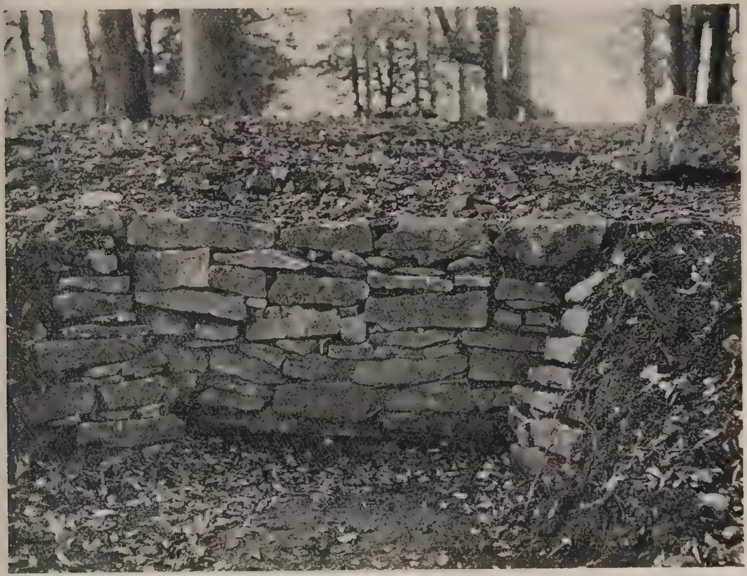

FIG. 211.—LIMESTONE IN A PREHISTORIC WALL.

Portion of the wall constructed of limestone enclosing the mound on which a dolmen at St. Nicholas, Glamorgan, was erected; it was built about 2,000 B.C.

Limestone in modern times.—Before proceeding to a review of the use of limestone through the ages it will be convenient to consider the present annual output, and the proportion of the total output that is taken by each of the industries concerned:—

OUTPUT AND USE OF LIMESTONE IN 1927.

	Tons.
Limestone and Dolomite :—	
For lime and cement making	3,999,000
,, use as flux in blast furnaces	3,023,000
,, building	507,000
,, road-making	5,027,000
Dolomite for use as a refractory material	580,000
Limestone for use in chemical industries	922,000
Limestone for use in glass-making	33,000
Limestone used for other purposes or not classified ...	320,000
Total for Great Britain	14,411,000

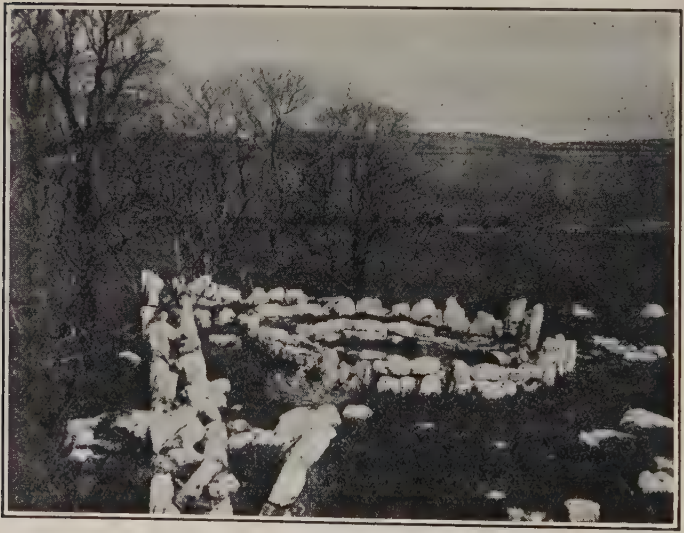

FIG. 212.—A CORNER IN AN ANCIENT BRITISH FORTIFIED VILLAGE.

Din Lligwy, near Dulas Bay, Anglesey; a group of circular huts was enclosed in a rectangular walled space, the stone used being Carboniferous Limestone: photograph by E. Neil Baynes, Esq., F.S.A., reproduced by permission of the Rt. Hon. Lord Boston.

From this it appears that, for the year in question, more than one-third of the limestone quarried or mined in this country was required in the making and mending of roads, nearly a quarter each for lime-works and cement-works on the one hand and blast furnaces on the other, leaving only about one-sixth for all other purposes; these proportions have not, however, always been the same. At one time, lime-making and building were almost the only uses to which limestone was put, and, as in the Middle Ages the smelting of iron and other metals grew in importance, blast furnaces entered the field as large consumers of limestone, but it was not until well into the last century that roadmaking was responsible for any large consumption of this, or indeed of any other stone. Once, however, the building of good roads commenced, traffic upon them increased and still better roads were demanded, with the result that roads are now responsible for the utilisation of nearly half the total limestone output of the country, for it must be remembered that in addition to the stone recorded as for "road-making," an appreciable amount of the limestone used in the manufacture of cement ultimately finds a use in road construction.

Limestone in building.—That the suitability of limestone as a building material was early recognised is seen in the use of Nummulitic limestone (see page 267) by the Egyptian builders of the Pyramids, and in the use of travertine and tufa by the Roman builders of the Colosseum; the early Greeks also took advantage of certain kinds of marble in which homogeneity and relative softness were combined with durability, and produced the sculptures for which they are so justly famous. The quantity of stone involved in the case of the Pyramids at Gizeh is enormous; built principally of limestone, except for the walls of chambers and passages, which were of granite, the largest of the three was 764 feet square at the base, and 480 feet high. Some of the limestone blocks were 35 feet x 5 x 4, and the three Pyramids together contain over one hundred and seventy million cubic feet of stone—an amount nearly equal to the total output of limestone for all purposes from Great Britain in 1927. Expressed in another way, the Great Pyramid alone contains sufficient stone for the erection of 10,000 dwelling houses each of 8,000 cubic feet capacity and with walls 1 foot in thickness [5].

The history of the use of limestone in building has yet to be written, and even for our own country that will prove no easy task, because, although used in buildings or parts of buildings of all ages from Roman times onwards, the records relating to its use are not sufficiently detailed to be of great assistance. Most of them relate to national or ecclesiastical buildings and to castles, and are in the nature of account-book entries and records of the quantity and cost of the stone used; for much of our information we are indebted to the monks, because in the Middle Ages they were almost the only people sufficiently well educated to keep records, and not too busily engaged in fighting to do so.

Casual reference to the employment of stone in past and present times has been made in connection with our discussion of the distribution and origin of the stones themselves, and certain other aspects of the subject that could not conveniently be introduced in earlier chapters are dealt with in the following notes.

In mediæval times most of the ordinary people lived in houses of earth or wood, and only important buildings were constructed of stone; naturally, owing to the limited means of transport, local stone was used wherever possible, although not exclusively. As examples of the use of local limestones by the Romans we may take the walls surrounding Cardiff Castle, where even to this day portions of their work, executed in Liassic limestone, are to be seen (see *Fig.* 77). Where importation was necessary, stone that could be brought by water was preferred on account of the difficulties of road transport. The Kentish Rag used in the walls of London and in many early buildings in the Metropolis was brought by water from the quarries near the Medway, and many centuries later, the extensive use of the Barnack Stone of Northamptonshire was due in large measure to the favourable situation of the quarries, between the Rivers Welland and Nen.

The Saxons, for the most part, made their dwellings and even their churches of wood, and so little use was made of stone that when, in the 7th century, the Abbot of Wearmouth was building an Abbey, he was unable to find men in this country who could build in stone, and he brought " artificers of stone houses and glass windows into the island amongst the Saxons." This we learn from Stow's " Survay of London "* (1598), where it is also recorded that in a charter granted to the Abbot of Malmesbury in 974, King Edgar complained that " all the monasteries in my realm, to the outward sight, are nothing but worm eaten and rotten timber and boards."

With the coming of the Normans, however, there commenced a new era in the use of building-stone, for in the centuries following the eleventh many of our greatest castles and sacred buildings were commenced. At this time, too, local or easily transported stones were generally used; for example, Kentish Rag in Rochester Castle, Carboniferous Limestone from Anglesey in Beaumaris Castle, Liassic Limestone, including the Sutton Stone in various parts of Glamorgan, the Oolitic limestone in the southern midland counties, and the flints and building-stone beds of the Chalk on various parts of the Chalk outcrop.

---

* John Stow, sixteenth century antiquary and chronicler, was the author of numerous historical works, including "*A Survay of London, contayning the Originall, Antiquity, Increase, Modern Estate, and Description of that Citie, written in the year* 1598."

One of the principal exceptions to the rule that local stone was used was the importation of Caen stone from Normandy; this was due no doubt to the fact that the Normans were aware of its valuable "freestone" properties by reason of which it could be carved and utilised for decorative work. As a matter of fact it transpired that native oolitic limestones were equally good as media for carving and were much more durable.

As far back as 1577 we find William Harrison, in his "*Description of England*," protesting against the importation of foreign stone, Caen stone in particular, and his words are so similar in sentiment to those freely expressed at the present day that they are worth quoting. He wrote :—

> "It farre passeth my cunning to set downe how manie sorts of stone for building are to be found in England, but much further to call each of them by their proper names. Howbeit, such is the curiositie of our countrimen, that notwithstanding almightie God hath so blessed our realme in most plentifull manner, with such and so manie quarries apt and meet for piles of largest continuance, yet our elders haue, from time to time, followed our naturall vice in misliking of our owne commodities at home, and desiring those of other countries abroad, most esteemed the Cane stone that is brought hither out of Normandie; and manie euen in these our daies following the same veine, doo couet in their works almost to vse none other."

Alarmed at the enormous consumption of wood in the making of bricks—for at that time the deforestation of this country had reached serious proportions—he also wrote in connection with stone :—

> "we are lothsome of this abundance, or not liking of the plentie, we doo commonlie leaue these naturall gifts to mould and cinder in the ground, and make up an artificiall brick, in burning whereof a great part of the wood of this land is dailie consumed and spent to the no small decaie of that commoditie, and hinderance of the poore that perish oft for cold."

The quarrying industry.—Stones for walling and similar purposes were originally obtained by selection from the loose debris associated with natural exposures and from the material brought up during ploughing, but such material naturally became scarce as time went on, and quarrying was more and more resorted to.

In the early days, the quarries were small and work in and around them was regarded as unskilled labour; as to the latter, in 1333 the quarriers at Tadcaster (Magnesian Limestone) received 1/4 per week, while the masons who worked the stone received 2/6, and in the Chalk quarries at Bisham near Maidenhead, worked in connection with the building of Windsor Castle in 1368, the " quarriers " received 3½d. per day [14].

The tools, also, were of the simple type that remained in use until the introduction of mechanical appliances for drilling and cutting stone. In the Magnesian Limestone quarries at Stapleton, Yorkshire, according to an inventory made in 1400, there were numerous iron wedges, crowbars, and hammers, and for a quarry at Launceston, the purchases (15th century) include " an iron tool for breaking stone in the quarry called a polax, weighing 16½ lb., and two new wedges weighing 10 lb."

From the nature of things, the primitive methods are often the only ones available in quarrying, except when working on a large scale. Although gunpowder was invented sufficiently early for there to be references to cannons in the stores at the Tower of London in 1388, it was not applied to the blasting of rock until early in the 17th century (1627, in Saxony), and in this country was not so used until about one hundred years later. An 18th century account of operations in the limestone quarries near Bristol is worth quoting, because, except for the present-day use of mechanical appliances for drilling and of explosives more effective than gunpowder, the methods employed were essentially like those of to-day.

Edward Owen in his " *Observations on the Earths, Rocks, Stones and Minerals . . . about Bristol* " (1754), wrote :—

> " They work here by blowing them up, for which they are allowed six-pence or seven-pence a ton, the master of them always finding tools and gunpowder. . . . Two people usually set about it at a time; one of them has in his hand the boring tool; this is an iron bar, formed at the point into a kind of chissel; the other has nothing but a hammer.
>
> The person who manages the boring instrument, takes first one of about two feet long, the point of which he fixes upon such part of the rock as he thinks will best suit his purpose; and the other strikes upon the top of it with the hammer, while he holds it steady. The blows are repeated; and the bar turned every time the person strikes, and being quite round, except at the point, it makes its way into the stone.
>
> When a little hole is made, they put in water and as they go on boring, they from time to time clean out the hole in the manner as people clean a gun-barrel. . . .
>
> When the hole is thus made of the depth they chuse, they clean

> it very well out, and make it dry. They then put in a quantity of gunpowder, . . . sometimes not more than half a pound and sometimes two or three pounds. When the powder is in, they thrust down a small wire reaching down to it and up to the surface. They then make up some very stiff clay, or other such matter, and ram it into the hole extremely firm, filling it entirely, and in the strongest manner possible. When the clay or other matter is well in, they draw out the wire; this leaves a little hole quite down to the powder at the bottom. They then fill up this hole also with powder, and lay a train of gunpowder from this. At the end of the train they lay a piece of lighted touch-wood, and leave it to take effect.
>
> It is their business to get away, for the effect is very violent. Several tons of stone are generally loosened by the blast, and frequently pieces of two or three pounds weight are thrown like cannon-shot to a considerable distance."

As transport facilities improved, the tendency to distribute stone from a few favoured localities increased, with a corresponding decrease in the number of small quarries, and the industry tended to become localised; this has become more evident since the development of railways in the early part of last century.

An account of the technique of quarry methods as applied to limestone would be out of place in a book like the present; see, however [6, 17-20]. Under modern conditions the engineer is being pressed into service to a greater and greater extent, not only in obtaining the stone from the quarry, but in preparing it for the purposes for which it is required, and in many cases the appliances for crushing and sorting stone (*Fig.* 213) are far more conspicuous features of the landscape than are the quarries themselves.

The Marblers of the Middle Ages.—The extent to which the limestones of the various geological formations have been or still are used as building stones has already been indicated, and the only matters of historic interest that need be recalled here, are the wide use of the easily worked oolitic and chalk freestones by the mediæval church builders, and the great increase in the use of Portland Stone during the 17th century.

An interesting, and at the time, important episode in the history of the stone trade in mediæval England was the rapid development in the use of Purbeck Marble for ecclesiastical decorative work. The rock was capable of receiving a high polish, and, with its dark colour, contrasted well with the light coloured freestones of which the main fabric of many buildings was then constructed; it was used largely in the form of shafts or small columns, and in effigies. It came into fashion towards

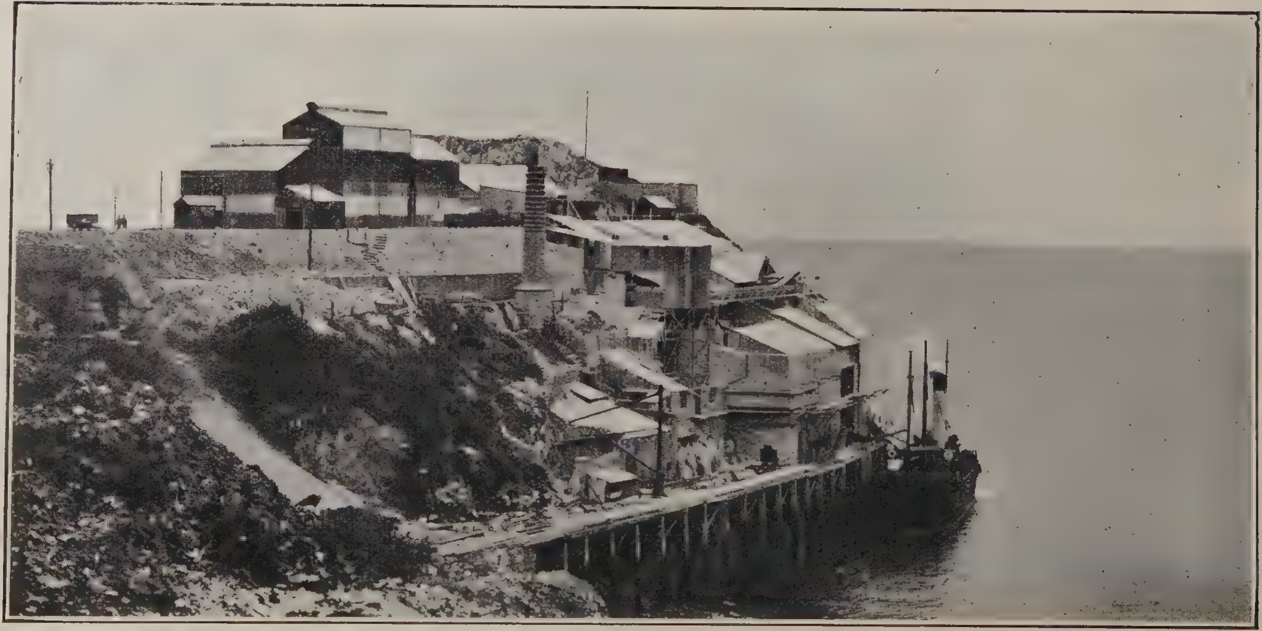

FIG. 213.—OUTSIDE EQUIPMENT AT A MODERN LIMESTONE QUARRY.

The crushing sheds and loading quay of a quarry in Carboniferous Limestone near Llandudno, North Wales. (Reproduced by courtesy of the Ship Canal Portland Cement Manufacturers, Ltd.)

the end of the 12th century, one of the earliest references to it dating from 1190, and relating to a quarry at Worth Matravers in the Isle of Purbeck; a few years later (1205) it was used in Chichester Cathedral.

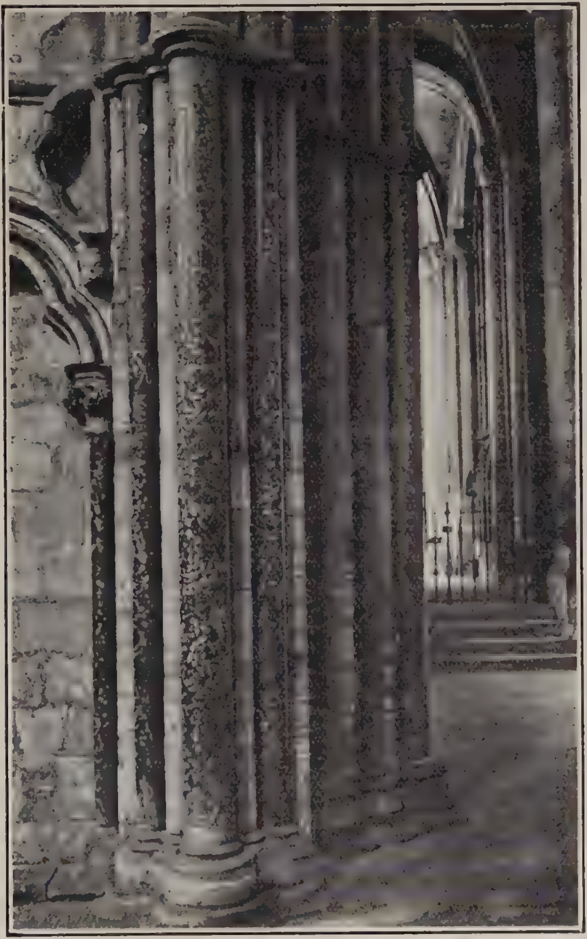

FIG. 214.—LIMESTONE USED FOR DECORATIVE PURPOSES.

Columns of Frosterley Marble, a coralliferous variety of the Carboniferous Limestone, in Durham Cathedral (thirteenth century): by courtesy of J. R. Edis, Esq.

Its use may possibly indicate the influence of the Byzantine style of architecture that arose in the Eastern Empire in the 6th century and continued for nearly a thousand years, and in which parti-coloured masonry was often used: a parallel is seen in the Auvergne region of France, where columns of black basalt were used in conjunction with pale coloured freestones.

Interesting information collected by the writer of the Victoria County History of Dorsetshire [7] throws light upon the state of the industry when in its heyday; for example, in 1279, the Sheriff of Dorset bought 300 columns of Purbeck Stone for use in a nunnery that was being built for the Countess of Arundel. Corfe, near Swanage, was the centre of the industry, and Adam of Corfe was a contractor in a fairly large way, for in the early 14th century he supplied paving stones for St. Paul's Cathedral and marble columns for St. Stephen's, Westminster; the cost of the latter was 6d. a foot.

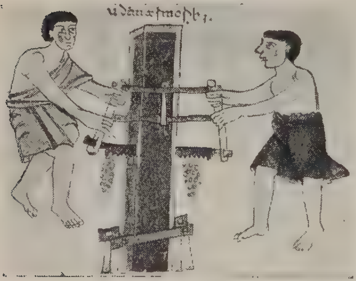

FIG. 215.—Sawing marble in the eleventh century

From the facsimile of a manuscript (dated 1023) in the University Library, Cambridge. (Reproduced by permission of the Librarian, and of the Clarendon Press, Oxford, and L. F. Salzman, F.S.A.)

Much of the work of cutting and polishing the stone, even the carving of effigies for tombs, was done at the quarry, and the images were probably for the most part conventional; in 1253, for example, Henry III. ordered "an image of a queen" to be cut in Purbeck marble for the tomb of his sister at Tarrant Keynston.

The influence of the "Marblers" of Purbeck spread to other parts of the country—for example, about 1280, craftsmen were taken to the north where they established a workshop at Durham. Much of their early work was in alabaster, and in the conventional style of the time, but at an early date the local "Frosterley marble," to which reference has already been made in connection with the Carboniferous Limestone (of which it is a coralliferous variety), was pressed into service, and was used for some of the effigies and much of the decorative work in Durham Cathedral (*Fig.* 214) and the churches of the district [8].

During the 15th century the use of Purbeck marble for decorative work went out of fashion, alabaster taking its place, and by the 16th century it was mostly used as building stone and for lime burning.

The weathering of building stones. — The reasons for the popularity of limestones for building purposes are that in addition to being comparatively light and easily worked, many of them are intrinsically beautiful. With certain exceptions, however, they are less suitable for external use in industrial towns than some other kinds of stone, on account of the solubility of calcium carbonate in waters that are acid or that contain carbon dioxide.

The air of industrial towns often contains compounds of sulphur derived from the smoke of coal, and these, in the form of sulphuric acid combine with calcium carbonate forming calcium sulphate. The waste gas from the burning of a ton of average coal contains from 30 to 50 pounds of sulphur, from which it will be seen that the amount of sulphurous vapours discharged into the atmosphere of a large industrial town is very great. If the effect of these gases upon limestone stopped with the formation of calcium sulphate little serious harm would be done because the product of the alteration is but slightly soluble in water, but the newly formed salt tends to crystallise, and since the volume of the crystals of gypsum is 20 per cent. greater than that of the calcite from which they were derived, the surface layers of the stone are shattered (*Fig.* 216), thus promoting the disintegration of the rock and the exposure of fresh material to the same destructive influences [9].

The process may be even more destructive in the case of dolomitic limestones, because the magnesium sulphate produced during the change is soluble in water, and its removal leaves the surface layers of the stone in a friable condition; this was illustrated in the case of the Houses of Parliament. The fact, mentioned on a previous page, that similar dolomitic limestone was also used at about the same time in the building of the Museum of Practical Geology, and has withstood well the ravages of the weather, indicates that the rock is not of necessity unsuited for town use, provided that, as was the case with the stone for the latter building, adequate experience is brought to bear upon the selection of the beds to be quarried and of the actual blocks to be used.

That changes, such as those described, are in progress, is often indicated by the appearance of a white powdery growth or florescence on the surface of the stone. The material, sometimes known to builders as "wall-white," usually consists of calcium, magnesium, and sodium sulphates, but its composition may in some cases be influenced by the associated mortar or cement [24].

The air near the sea contains common salt (sodium chloride) and the rain water small quantities of chlorine, so that in such situations the destruction of limestone is hastened because both those substances facilitate the solution of calcium carbonate in water charged, as rain water always is, with carbon dioxide. Moreover, sodium chloride is deliquescent, that is to say it "melts" in the moisture it absorbs from the air, so that in moist

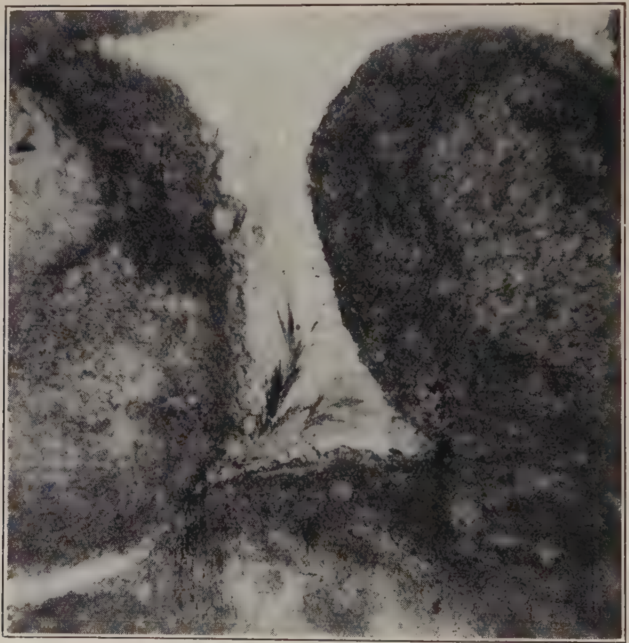

FIG. 216. — PHOTOMICROGRAPH OF A SECTION OF WEATHERED PORTLAND STONE FROM THE TOWER OF LONDON.

The photograph shows crystals of gypsum growing into the cavity between three oolitic grains: magnified 150 diameters. (Reproduced, by permission of the Controller of H.M. Stationery Office, from the Report of the Stone Preservation Committee, 1927.)

air, stone on which common salt has been deposited tends to remain damp, or, should dry conditions cause the evaporation of the water, the salt, in crystallising, has a disintegrating effect upon the stone, just as in the case of gypsum.

The United States Bureau of Standards has conducted experiments to ascertain the extent of the solubility of limestone in rain-water. Two-inch cubes of rock were exposed on the roof of the Bureau's building at Washington, and after careful weighing spread over a period of about 7 years, it was found, that from exposure to the weather, an oolitic limestone would lose a layer about 1 millimetre in thickness in 100 years. The loss from a compact crystalline limestone was about one-third less, and the loss in each case was, no doubt, less than would have been sustained in the atmosphere of an industrial town. Another investigator, F. Pfaff, found that a slab of Solnhofen Limestone, with an area of 2,520 square millimetres, lost by the solvent action of rain 0.548 grams in 3 years. In cases where the limestone dissolves in such a way as to give rise to a rough surface, dirt tends to accumulate more readily than when the rock is uniformly soluble and the weathered surface remains relatively smooth [15].

Theoretically, dolomitic limestone should resist the solvent action of rain water more than pure limestone, for, under similar conditions calcite is more soluble than dolomite, but, as we have already seen, dolomitic limestones frequently have a coarse granular texture and are somewhat porous—properties which allow water greater freedom of access to the surfaces of the particles of which the rock consists, and so facilitate solution.

The effect of water in promoting the decay of building stones was very early recognised, and, of the expedients adopted to carry the water away from the walls, the gargoyles, which eventually became so ornamental that their original function is scarcely apparent, are among the most interesting.

The complicated nature of the process of building-stone destruction becomes very apparent when it is realised that in spite of the disintegrating effect of rain water and its gaseous contents, stones that, from their position in buildings, are frequently rain-washed, usually decay less readily than those in protected situations: the cornice of St. Paul's Cathedral, for example, was found by Sir A. H. Church to show signs of much greater destruction on the south side of the building than on the north [21]. This is because on exposed faces, especially if they are vertical, the rain tends to wash away the dirt and to remove the products of alteration before they crystallise, whereas under cornices and in places seldom or never reached by rain, the shattering effect of crystallisation proceeds unhindered, and the friable surface thus produced facilitates the entry and retention of acid-laden moisture.

Snow also plays a part in the destruction of limestone in regions where it is at all prevalent, because, as a rule, carbon dioxide and other "atmospheric" acids are relatively more abundant in snow than in rain water.

The effect of frost in shattering rocks is very apparent in high altitudes and in arctic regions, but it also contributes to the destruction of building stones in comparatively temperate regions, not only by its direct effect upon the rock, but also in the way in which it facilitates the work of other destructive agencies. It is a well known fact that the volume of ice is about one-tenth greater than that of the water from the freezing of which it results, so that if a stone is nearly saturated with water, freezing will tend to force its particles apart, for, not only does the ice occupy more space than the water, but the change from one condition to the other is accompanied by sudden expansion, exerting a pressure of nearly 140 tons per square foot. Fortunately, rarely, if ever, are the pore-spaces of a rock completely filled with water under natural conditions, or no rock would withstand the action of frost, but *local* disintegration from this cause often takes place. It is not so much the magnitude of the total pore-space of a stone as the extent to which the pores can be filled with water and the ease with which the water can pass through the rock that determines its resistance to frost action. For example, the oolitic Ketton Stone is very porous and has but little cementing material between the grains, and yet it withstands frost action better than the associated Ketton Rag, which is heavier, harder, and has a matrix of well crystallised calcite between the grains; this is because the nature of the porosity of the oolite is such that as a building stone the pores are never completely filled with water, and the pressure exerted by freezing water is dissipated [21].

Although in the open country lichens and mosses play an important part in promoting the disintegration of rocks, in towns the former are rarely met with and the latter do not usually flourish on rock surfaces that are exposed in buildings. Lichens attach themselves by fine hair-like "hyphæ" that act the part of roots and that penetrate into minute cracks in the stone. In the case of a calcareous rock, the acids produced during the growth of the plant dissolve portions of the stone, and, quoting from erner von Marilaun, who investigated the relation of lichens to ock decay,

> "a growing hypha penetrates wherever the merest particle of carbonate of lime has been dissolved, and accomplishes regular mining operations at the spot. Particles of the carbonate not yet dissolved are separated by mechanical pressure from the main mass, and at the places where a lichen is in a state of energetic growth tiny loose fragments (of calcite) are seen, which are washed away by the next shower or else are carried off as dust by the wind."

Only relatively hard and durable rocks can support lichens which are rarely, if ever, seen on those that are soft and crumbly, nd it has been remarked that "if a stone is so liable to supercial crumbling that lichens cannot ensconce themselves, it has no usiness on any building" [21]. The rarity of lichens in inustrial towns is, no doubt, due to the fact that the acid-laden tmosphere and the other "urban" agents of destruction prouce a crumbly surface on stones that in rural areas afford an deal habitat for those lowly but interesting plants.

The known fact that bacteria play a large part in the formaion of soil from rock debris suggests that bacteria may also, in ome cases, be responsible for the decay of building stones, and he matter has received the consideration of the Stone Preservation Committee of the Department of Scientific and Industrial Research. At least twelve different kinds of bacteria were found n various samples of weathered stone, and the report continues :—

> "On isolating the bacteria from certain specimens of weathered stone, the colonies which developed on the plate were all of one kind. This fact, sufficiently significant in itself, was rendered still more so when on investigation of the characteristics of this species, it was found capable of making luxuriant growth upon an artificial medium so poor in organic food material that the life of other bacteria was barely supported. This instance alone encourages the belief that a full investigation of the biological aspects of stone decay is warranted and should be pursued with the utmost vigour" [10].

It would seem that limestones are specially subject to bacterial decay, for the organisms derive their nourishment from the nitrogenous compounds, such as ammonia, present in rain water, and he ammonia is converted into nitric acid which readily dissolves calcareous rock or cementing material [11]; this process accounts for the decay of limestones and calcareous schists in the highest Alpine regions where no life exists, except certain kinds of bacteria [12].

Bacteria also decompose organic matter, setting free carbon dioxide, which, as we have previously seen, converts water into a weak acid capable of dissolving limestone.

In the foregoing notes the agencies tending to the destruction of limestone have been discussed, because this work is primarily concerned with that kind of rock, but it must not be supposed that limestones are specially susceptible to the ravages of rock weathering and denudation, for the processes which tend to destroy limestone also operate in the destruction of rocks such as sandstone and conglomerate when the constituent particles are held together in a matrix of calcareous material, and the minerals of igneous rocks are decomposed by the same agents. Indeed, long experience has shown that Portland Stone resists atmospheric action in places like London, better than most other stones, and instances of its use have already been given.

The preservation of building stones. — From what has been said it will be realised that the essential feature in any method that may be adopted with a view to inhibiting stone decay or retarding its development depends upon preventing the access of water to the pore spaces in the surface layers of the stone, and these, in the case of many building limestones such as the oolites, are often of importance.

The value of paint as a preservative has long been recognised, but apart from its expense and the necessity for frequent renewal, it obscures the character of the stone, and recent work has been done in the direction of finding a preservative that would protect the stone without causing an apparent change in its appearance.

Various media, such as sodium silicate, have been tried with a view to sealing the surface pores in order to keep moisture from penetrating into the stone, but when an impermeable crust has been formed there is a tendency for it to expand independently of the rock beneath, resulting in fracture and scaling.

If a material like paraffin is applied in such a way as to coat the grains without filling the pore spaces, the access of moisture is prevented without introducing difficulties consequent upon expansion, but such treatment is expensive, and a similar result has been obtained by Professor A. P. Laurie with " silicon ester "—a substance prepared by the action of alcohol upon silicon tetrachloride—which coats the grains with silica that is practically insoluble in water [13].

Processes involving chemical reactions have also been devised; for example, in the restoration of the Chapter House at Westminster Abbey, built of Reigate Stone, the grains of which were held together by calcium carbonate, a solution of barium hydrate was sprayed on to the weathered surface (spraying was resorted o on account of the extreme friability of the stone). The gases present in the atmosphere had converted the calcium carbonate nto calcium sulphate (gypsum), to which change the disintegraion of the stone was due, and the combination of that substance with the barium hydrate produced insoluble barium sulphate and eft the calcium of the gypsum in the form of calcium hydrate; his, combining with the atmospheric carbon dioxide, formed a resh cementing material of calcium carbonate in the pores of the tone [16]. Unfortunately, the decay of the stone had proceeded oo far for the process to be successful, as the newly-formed crust ended to flake away.

Accounts of other methods that have been tried, and of the rend of recent research in the matter of stone preservation—especially in relation to limestones and other rocks with calcareous cementing material—will be found in the report of the Stone Preservation Committee to which reference has already been made; see also [25], and Additional Note, page 453.

The “seasoning” of building stones. — The fact that the extent to which a stone will resist decay is often dependent upon he facility or otherwise with which water can gain access to its pore spaces, prompts a reference to a process whereby Nature herself provides a means of protection to quarried blocks of stone.

We have already seen that from their mode of origin the particles of sedimentary rocks are separated by spaces (unless recrystallisation has resulted in the deposition of additional mineral matter between the original particles) and that under natural conditions in the earth's crust the pores are more or less filled with water. Now when a block is quarried out, the contained water evaporates and tends to travel surface-wards, bringing with it mineral salts that may be dissolved therein, or minute particles of clay that may be in suspension. These materials, deposited between the grains at the surface of the blocks where the evaporation takes place, tend to fill the pores and to bind the particles more closely together, forming a kind of crust that may, according to circumstances, be comparatively thin or may extend for a considerable distance into the stone. This process, known as “seasoning,” has been mentioned in connection with the hardening of rocks like Beer Stone and some of the oolites after they have been quarried, and provides an explanation of the fact that in many cases it is easier to work freshly quarried blocks than those that have been for long exposed to the weather. It also has a bearing upon the durability of the stone when in use, for if cut and worked long after the seasoning has taken place, and in such a way as to expose the inner, non-indurated stone, the latter will have very poor weather-resisting properties. Failure to recognise the importance of the process of stone-seasoning has sometimes led to disastrous consequences, for, " a wise builder does not furnish the interior of his house with fittings of ' green ' timber, neither should he construct the exterior with ' green ' stone " [23].

A recognition of the risk incurred by dressing stone in such a way as to remove the " seasoned " layer, is probably indicated in the reference made by Josephus to the fact that Solomon's temple was built without noise, a circumstance commemorated in Reginald Heber's *" Palestine "* (1803) :—

> " No hammer fell, no ponderous axes rung;
> Like some tall pine the noble fabric sprung :
> Majestic silence ! "

The main building was constructed of white marble that gleamed in the sun (1 Chronicles xxix., 3) and that contrasted with the darker native stone (probably Tertiary Nummulitic limestone) that was used in the surrounding cloisters.

Very little is known concerning either the process or the results of " stone seasoning," and some authorities are of the opinion that after adequate exposure, it is *desirable to remove the outer layers* during the process of dressing the blocks [25]. They argue that the stone in its natural bed is saturated with water containing salts derived from the soil or other superficial deposits through which it has percolated, so that when, in the quarried block, the water tends to move surfacewards and evaporate, crystals are deposited in the surface layers of the stone. Such crystallisation may lead to disintegration, and it is said, it may be desirable to allow the blocks to " season " until most of the dissolved mineral matter has been deposited in the surface layers which are then removed when the stone is dressed for use.

Until the precise composition and function of the " quarry-water " has been investigated, however, the " seasoning " of stone can neither be properly understood nor adequately taken advantage of.

The testing of building stones.—In many cases a particular kind of rock has been so long in use that its strength and durability under all kinds of conditions are well known as a result of actual observation, but when a rock is to be used under hitherto untried conditions, or when it is proposed to use a variety that has not before been quarried, laboratory tests are often useful and sometimes necessary in order to indicate its possible behaviour. A detailed account of the testing of building stones would be out of place in the present work, and it is sufficient to say that the tests applied are usually directed towards ascertaining such properties as the weight the stone will withstand without crushing, the strain to which it may be subjected without breaking, and its re-action to water and to frost [21, 22].

The resistance to crushing is determined by squeezing rectangular blocks from two to four inches square in a vice-like machine that records the breaking pressure, but such a test is really only comparative, for while the crushing strength of limestone may vary between 100 and 1,000 tons per square foot, the load on a stone in a building is rarely more than 10 or 12 tons per square foot; see Appendix IV, page 443.

The tensile strength or resistance to direct strain is determined by means of a machine that records the breaking point of a small block that is being stretched. Here again the value of the evidence is indirect, for although any rock that could be used for construction would withstand strains far beyond those to which it is likely to be subjected in practice, severe internal stresses often result from the action of frost and changes of temperature, and in the hands of a competent observer the behaviour of the stone during the testing operation may yield evidence of greater value than the figures obtained as a result of the test. Many other physical properties of stone can be examined and compared by means of laboratory tests, but it is necessary to bear in mind that the results of such tests are apt to be misleading, except in the hands of those trained to interpret them.

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CHAPTER XVI.

LIME AND LIMEBURNING: MORTAR AND CEMENT.

> "If we are . . . to hold our own, and to . . . perfect our manufactures, to bring new departments of nature into the service of man, it is by broad, thorough, untrammelled scientific research that our success must be achieved."
>
> SIR A. GEIKIE, in an address at the opening of the Mason University College, Birmingham, in 1898.

Lime through the ages. — Lime must have been discovered soon after man learned to make fire and used stone for building his hearths and fireplaces, and although its valuable properties were probably wasted on primitive man, at a very early date it was brought into use in connection with the erection and decoration of buildings.

Some of the chambers in the Pyramids, belonging to a period about 2,000 B.C., contain the remains, in good preservation, of ime-plaster or stucco, and in other early Egyptian buildings, ath-and-plaster construction has been observed—lime-plaster being used in conjunction with reed "laths." The surface of the plaster work was often "finished" by the addition of a layer of gypsum-plaster, decorated with colour or ornament.

The Greeks also used lime-plaster for the decoration of their temples, even when the stone used was marble, and it was much favoured in Rome and other parts of Italy. For a good deal of our information relating to these early periods we are indebted to Pliny the Elder (Gaius Plinius Secundus), whose "*Natural History*"—compiled a little before his death, which occurred in A.D. 79 during the eruption of Vesuvius that destroyed Pompeii and its sister city—is a veritable encyclopædia of contemporary knowledge [1].

He tells us, for example, that in the Greek temple at Elis (B.C. 450) lime plaster mixed with milk and saffron (in order to give it a yellow tint) was used, and in Rome, at the beginning of the present era, plaster work was much used in external house decoration. The Greeks ground their lime very fine, beating it with wooden pestles, and Pliny pointed out that "no builder should employ lime which had not been slaked for at least three years."

The Romans also were particularly careful in the choice and preparation of their materials, and when one considers the remarkable state of preservation of their buildings, where they have not been destroyed in warfare or used as " quarries " by later builders, one is led to wonder what they would have been able to accomplish had they the advantage of many modern methods of construction [22a].

Although the early Greeks and Romans were familiar with the properties and use of lime, chemical knowledge was not then sufficiently advanced for them to explain the phenomenon of slaking. Pliny wrote : " It is something truly marvellous that quicklime, after the stone has been subjected to fire, should ignite on the application of water." The matter remained a mystery for many centuries, for Joseph Moxon in his " *Mechanick Exercises* " (1678) to which we shall have occasion to refer later, drew attention to the fact that " The fire in *Lime* burnt asswages not, but lies hid, so that it appears to be cold, but Water excites it again whereby it slacks and crumbles into fine powder."

Another Roman writer to whom we owe much knowledge of the use of lime for plaster and other work is Vitruvius (Marcus Vitruvius Pollio). An architect and engineer, he was the author of a work on building ; it was dedicated to Augustus and for many centuries was lost, but after its re-discovery at St. Gall in Switzerland, in the 15th century, it exerted much influence on European architecture until comparatively recent times. Vitruvius described the making of lime and its use in mortar and plaster ; for fine internal work a plaster consisting of lime and ground marble was used, and after much rubbing it became very hard and acquired a polish.

At a very early date, definite opinions were formed concerning the relative values of the different kinds of limestone for the making of lime. Pliny, for example, says :—

> " Cato* . . . disapproves of lime prepared from stones of various colours ; that made of white stone is the best. Lime prepared from hard stone is the best for building purposes, and that from porous stone for coats of plaster."

As far as the Romans were concerned the comparison between hard stone and soft stone was that between the soft porous tufa and the hard compact travertine to which reference has already

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*Cato (Marcus Porcius Cato), who lived from 234-149 B.C., was a Roman statesman and writer ; his works include a treatise on agriculture (*De R* *Rustica*) in which he gives rules for good husbandry and describes some of the customs of his time.

een made; the latter made very good lime, to which is due in art the strength and durability of Roman cements and mortars.

Similar views were expressed from time to time by those who wrote upon the subject. Joseph Moxon [2], a contemporary of Sir Christopher Wren, mentions two sorts of lime—stone lime (the strongest) used for external plastering, and chalk lime (better suited for internal use). He wrote :—

> " That made from a greasy clammy stone is stronger than that made from a lean poor stone; and that which is made of spongy Stone is lighter than that made from firm and close stone."

A century later, Edward Owen, in his " *Observations about Bristol,*" 1754, to which reference has already been made, expressed a similar opinion; he wrote :—

> " The lime that is made out of these (*i.e.*, the Bristol limestones —the Carboniferous Limestone) . . . when made into mortar is not so well coloured as what we have at London, but it is much superior in its qualities. We have our lime here made of chalk, but the Bristol lime, which is made out of this hard stone makes a much stronger mortar."

In this country, the use of lime declined with the wane of the Romans' influence, because at a time when stone was not much used for building, the demand for lime would be small, but the coming of the Normans inaugurated a fresh period of building with stone, and lime-burning again became important. It was used not only for mortar but for plastering. After a fire that destroyed London Bridge in 1212, King John issued a command that all houses and shops on the Thames—for the most part constructed of reeds and rushes—were to be plastered inside and out within eight days. The lime-plaster was put upon the wall which consisted of clay mixed with straw daubed upon the framework of wattles or hazel sticks interwoven with laths of oak or beech; later on, thin laths of oak or beech were used instead of wattles, and lath-and-plaster walls were customary in the better class houses, although for ceilings, plaster did not come into general use until the 16th century.

Plaster also played an important part in the external decoration of the half-timbered houses that are so characteristic of certain parts of rural England, and except in the matter of refinement, the use of lime-plaster for building has undergone but little change for many centuries and does not call for further comment here.

Lime-burning.—At first lime was " burnt " in small pits into which the limestone and fuel were put, but as its importance increased, kilns were built in which larger quantities could be dealt with, and in which the material was under greater control. For example, there is a 1396 reference to a " lympitte " in the Isle of Thanet, while in 1440, 3,300 bricks were used in building a kiln at York.

Originally most kilns were of a temporary character, such as those erected for the burning of lime for a single building; but when permanent kilns were put up they were often of considerable size; there are sixteenth century references to kilns that were 20 feet high and cost £50 each.

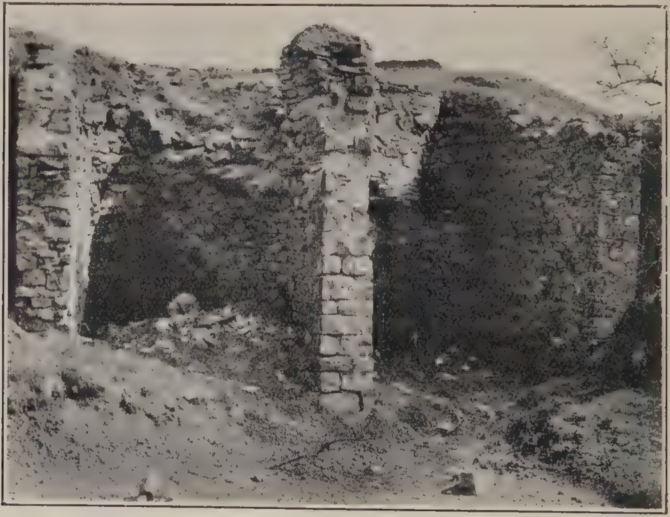

FIG. 217.—OLD LIME KILNS,
on an outcrop of Carboniferous Limestone south of Caerphilly, Glamorgan. (*Photo W.E.H.*)

Lime, being much more difficult to store or transport than limestone, was usually prepared where it was to be used—a practice that continued until well into the last century and accounts for the very large number of disused and ruined lime-kilns dotted about the country (*Fig.* 217), some upon or in the neighbourhood of limestone outcrops, and others far removed from any source of that rock.

Instances of old kilns on limestone outcrops have been cited in connection with the limestone in the Ordovician rocks of Wales and the Old Red Sandstone of Monmouthshire, and of kilns in places where no limestone occurs, in connection with the Devonian limestones of South Devonshire. Old kilns are often to be seen near small harbours and creeks accessible to coasting vessels; the remains of such a group are to be seen, for example, by the side of the harbour at Solva, near St. David's, and there are others on Ramsey Island and Skomer Island off the Pembrokeshire coast. Like many other small islands these were, at one time, more extensively farmed than at present, and since it was not expedient to carry lime for any distance, limestone was conveyed from the mainland and burnt from time to time upon the islands: the practice has long since been discontinued.

George Owen, the Pembrokeshire historian, to whose writings reference has already been made, and whose account of the distribution of limestone in South Wales, written in 1595, is the earliest instance in this country of an attempt to define the outcrops of various strata, described the manufacture and use of lime in his time. He wrote

> "this lymestone beinge digged in the quarey in great stones is hewen lesser to the biggnes of a mans fist & lesse, to the ende they might the sooner burne throwe, and beinge heawed smale the same is putt into a kill made of wall sixe foote heighe fowre or five foote broade at the bryme but growing narower to the bottom, havinge two lope holes in the bottome which they call the kill eyes; in this kill first is made a fier of Coales or rather colme* which is but the dust of the coales which is laid in the bottome of the kill, and some few stickes of wood to kindle the fier, then is the kill filled with these smale hewed peeces of lymestones, and then fier beinge geaven, the same burneth for the space of † and maketh the lymestones to become meere red fierye coales which being don and the fier quenched the lyme so burned is suffered to coole in the kill and then is drawen where it is laied in heapes and the next showre of rayne maketh it to Molter and fall into dust which they spreade on the lande, & so sowe wheat or barlie therein as the tyme of the yeare requireth."

He further added :—

> "This trade of lyminge hath ben more used within these thirtie or fortie yeares then in times past and it destroyeth the ffurse, fearne, heath and other like shrobbes growing on the land and bringeth forth a fine and sweete grasse and quite Changeth the hue and face of the grounds and hath greatlie enriched those that used it."

At first wood was the principal fuel, but the lime-burners made such serious inroads into the country's timber resources that at an early date coal was utilised for the purpose—lime-burners and smiths were, indeed, among the first to make any serious use of coal in this country.

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* Now called culm, a friable powdery coal common in parts of the Pembrokeshire Coalfield.

† A space occurs here in the original manuscript.

As an instance of the enormous consumption of wood in the burning of lime, we may cite a record (dated 1255) that two lime-kilns in the Forest of Wellington had "devoured" 500 oaks between them, and, as an example of the early use of coal, a record (dated 1278) that over 1,100 quarters of coal were brought to London for use in the lime-kilns at the Tower.

Lime-burning was naturally an important industry in and around London in the Middle Ages when the use of stone for building was steadily increasing, and, as was the custom among the merchants of the time, the vendors of lime tended to congregate in one part of the City. Sea Coal Lane, near Ludgate Circus, was so called in the 13th century (Sacoles Lane) because it was there that the vendors of Newcastle coal conducted their business, but the street was often referred to as "Limeburners Lane," for a good deal of the colliers' business was with those who required fuel for kilns.

The smiths had also been using coal, and early in the 13th century it was adopted by the brewers; very large quantities were used and Stow tells us that the citizens of London were so offended at the "sulpherous smoke and savor of the firing" that Edward the First "prohibyted the burneing of sea coale in London and the suberbs." The penalty for disregarding the order was the destruction of the kilns or furnaces, but it served only as a temporary check upon the use of the new fuel, because by 1329 its use for lime-burning had again become general in London. In that year, Hugh de Hecham, who figures as a colliery owner in Newcastle and a "lymbrennere" in London, was charged before the Lord Mayor in connection with an attempt made by the lime-burners of London to form a ring in order to raise the price of lime, and he was committed to prison.

Many years later (1528) Cardinal Wolsey wrote as follows to the Chancellor of the Bishopric of Durham asking for a supply of coal for the lime-burners at Ipswich, where a college was being built :—

> "Forasmoche as the maister of oure werks . . . is mynded to brenne great quantyte of lyme near unto our syed college, for which purpose it is requisit that a good quantite of see coolis be provyded fore by fore hand . . . we therefor woll that ymmedyatly upon the syght of thes oure letters ye doo ship and send thydder two hundred chaldis of oure owne coolis, and *that the sayde coolis be shipped of the best and largest measure used at Newcastell upon tyne.*" (The italics are not in the original.)

The local importance of lime in the early part of the 17th century is indicated by a reference in the Calendar of State Papers to a petition from "Jane, widow of Nich Darcy (of Newmarket) to the King, for a grant of the benefit of transportation of all manner of lime, burnt and slacked, limestone, chalk, etc. . . . in recompense of the services of her late husband to Queen Elizabeth." The request was, we find, rejected on the ground that it would establish a monopoly.

Practically all the limestones suitable for burning into lime have been pressed into service, and many of the smaller outcrops, that are now worked out or neglected (such, for example, as those in the Ordovician rocks of Wales and the Old Red Sandstone of the Welsh border counties) were formerly of considerable importance.

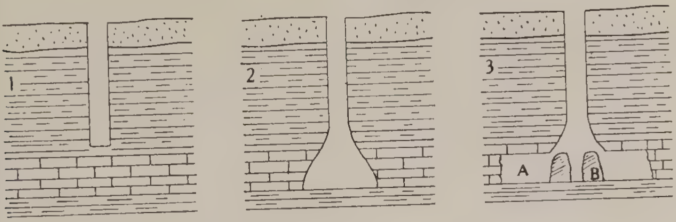

FIG. 218.—"BELL PITS."

Diagrams illustrating the nature and construction of "bell pits"; A, section along one of the passages radiating from the central cavity; B, the entrance to another passage

As an instance of the methods employed in the case of a stone that is no longer exploited, we may take the case of the limestones that occur in the Purbeck Beds near Heathfield and Battle in the Weald [4]. These were worked until early in the last century, but, owing to the mode of occurrence of the beds, open quarrying was not possible, and the method adopted was essentially similar to that in vogue in certain early coal mines. There were two main groups of limestone beds,—"Greys" consisting of limestone with beds of shale, altogether about 40 feet thick, and "Blues" consisting of limestone and shales, altogether about 25 feet thick: some of the limestones were used for lime-burning, others for paving or building.

Where the strata were flat or only gently inclined, and the limestone beds were situated at some distance beneath the surface, "bell-pits" were sunk; *Fig.* 218. The first operation was the making of a circular shaft, about 4 feet in diameter and about 20 feet deep; this was then "belled" out by increasing the diameter as the pit became deeper, until at a depth of 50 or 55 feet the diameter was 20 feet. Galleries, more or less horizontal, according to the inclination of the beds, were then driven radially from the base of the pit into the rock, and the excavated material was raised by a windlass. Where the dip was steep or the beds were more deeply buried, levels were driven into the hillsides to meet the strata, and adits for drainage were constructed, just as in the case of early mines for other materials, or indeed, modern mines where such methods happen to be more convenient than deep shaft-mining.

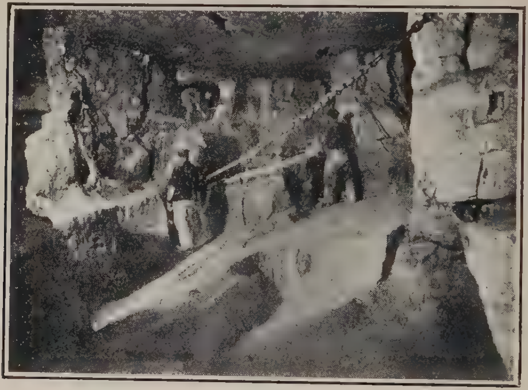

FIG. 219.—A LIMESTONE MINE.

Underground workings in oolitic limestone near Bath; by courtesy of United Stone Firms, Ltd.

Owing to the increasing demands made by the iron-workers and the lime-burners, wood fuel began to grow scarce in the sixteenth century; in the Weald, coal was difficult to get because the buried Coal Measures of Kent were then unsuspected, and in any case the coal could hardly have been reached and raised to the surface by means of the appliances then available; we find, therefore, that in the eighteenth century the fuel used in the lime-kilns was principally faggots and furze; the latter was specially grown for the purpose, being cut every two or three years.

The price of the lime at the beginning of the 19th century was 9d. a bushel for building lime and 8d. for agricultural lime, and the average annual output (1797) was 120,000 bushels. The kilns were in operation as late as 1816, but soon after that, trade in the Purbeck Limestone lime ceased, owing to the adoption of chalk lime as means of transport improved. Most of the lime used in London was made from Chalk from the neighbourhood of Gravesend.

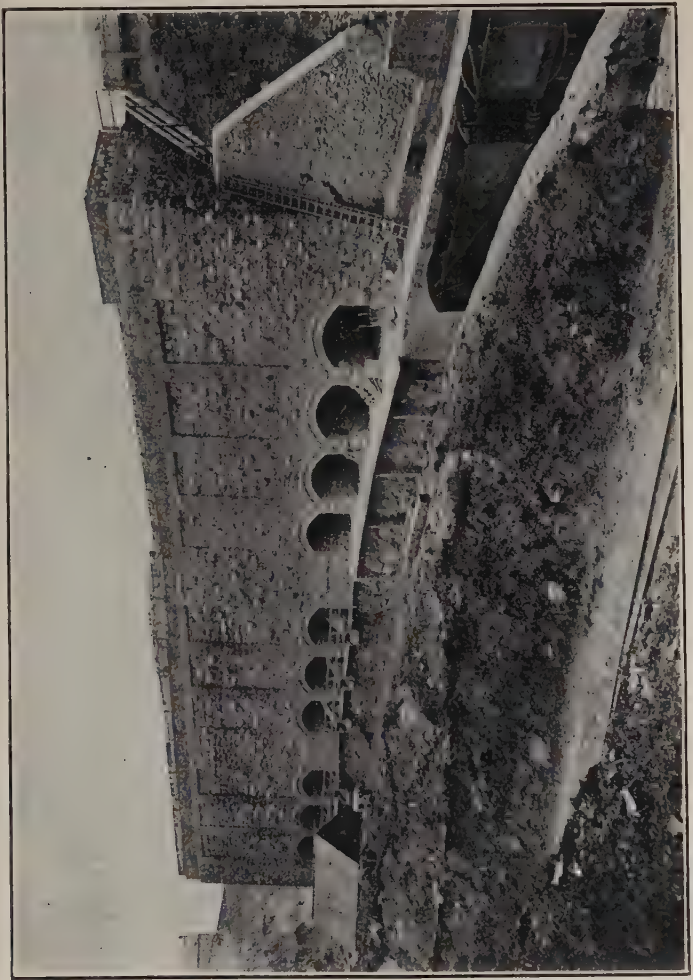

FIG. 220.—A BATTERY OF LARGE "OPEN" LIMEKILNS.
At Fulwell, near Sunderland; by courtesy of Sir Hedworth Williamson's Limeworks, Ltd.

Limestone is still obtained from underground " mines " i many places: this is the case for example with certain of th oolitic building stones of the Bath country (*Fig.* 219), with th Purbeck Stone in the Isle of Purbeck, and with the Wenloc Limestones at Rushall, near Walsall. The extensive limeston mines of Dudley have already been described.

Originally, the kilns in which lime was burnt were all intermittent in their action, that is to say, they were loaded, the contents fired, allowed to cool and the lime withdrawn, after whic the process commenced all over again.

Such a method is convenient where small quantities only are dealt with and the lime is needed at irregular intervals, but it is obviously wasteful of heat, and in modern practice the tendency is towards the use of kilns that are continuous in their operation. In the case of one " continuous " method, for example, a vertical kiln is fed with fuel and limestone in alternate layers, and as the lime is removed from the bottom, fresh raw material is added at the top, the " burning " proceeding as the mixture slowly descends through the kiln; *Fig.* 220. Other kinds of continuous kiln are in use, and in some of them the fuel—coal or gas—is burned outside the chamber in which the limestone is placed, so that the fuel and the lime do not come into contact; *Fig.* 221 [5, 6].

The " gas " fuel used is of the type known as " producer-gas "; that is to say, a gaseous fuel made from coal or coke in a " gas producer " in such a way as to yield a gas that will burn and leave no combustible residue. An essential constituent of all the varieties of producer-gas is Carbon monoxide (CO), which on burning, forms Carbon dioxide CO_2. Descriptions of the manufacture and uses of producer-gas will be found in the appropriate text-books [7].

The Rotary Kiln (*Fig.* 222) mentioned elsewhere in connection with the manufacture of Portland Cement has also been applied to the manufacture of lime, using gaseous fuel. The lime so produced slakes very rapidly and is, therefore, better suited for chemical or agricultural use than for building purposes.

Limestone begins to give up its carbon dioxide at a temperature of about 750°C, but the decomposition is not usually completed below 900°C; in the case of a magnesian limestone the temperatures are somewhat lower. Lime-burning is by no means a simple operation, for, if too strongly heated, impurities of a clayey or siliceous character will combine with the lime, forming complex silicates of the nature of slag, giving rise to a hard

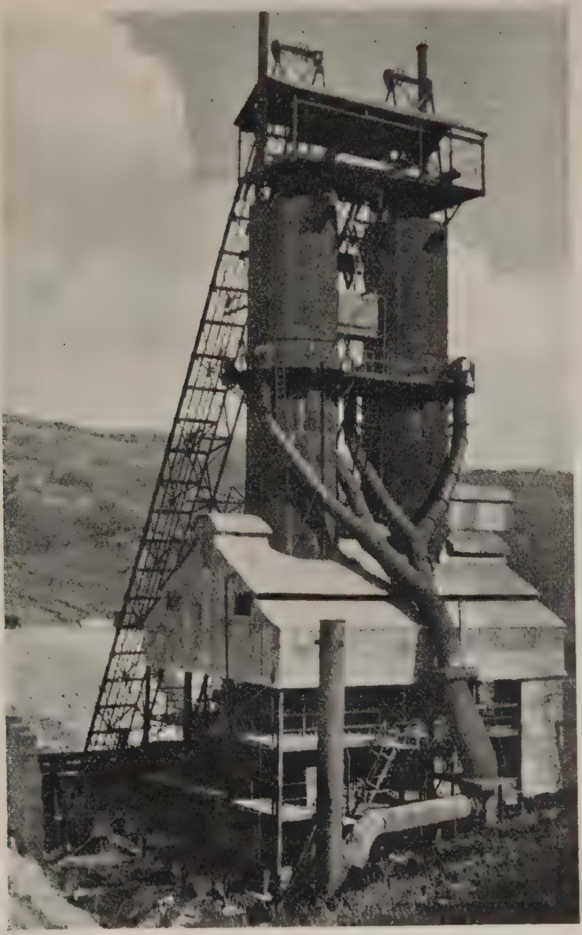

FIG. 221.—A MODERN LIME-BURNING PLANT.

The plant comprises two continuous vertical kilns (using "producer gas" fuel), together with the necessary accessory appliances, and has an output of 450 tons of lime per week; by courtesy of Priest Furnaces, Ltd., Middlesbrough.

stony lime that slakes slowly and imperfectly; while, unless it is possible for the carbon dioxide to escape readily as it is evolved, there is a risk of reproducing calcium carbonate, and in an atmosphere of carbon dioxide, calcium carbonate does not decompose, but fuses and yields a crystalline marble-like substance.

If the masses of limestone are too large there may remain internal " cores " of unaltered or partially altered rock that would make their presence known during the process of slaking, and are, for some of the uses of lime, objectionable.

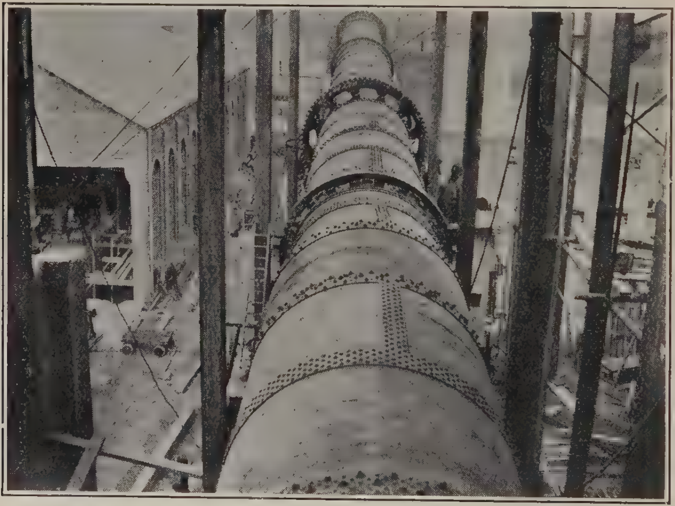

FIG. 222.—A ROTARY KILN FOR CEMENT MAKING: in the course of erection in South Wales.

Hydrated lime.—For most purposes, lime was formerly slaked by adding water to piles of quicklime and turning the heap by hand, and the quality of the product depended in large measure upon the skill and judgment of the workman.

The amount of water that actually enters into the combination is 18 parts (by weight) to 56 of quicklime, but during the process so much heat is evolved that (unless the mixture has been " drowned " by a great excess of water) some of the water may be driven off as steam, and more than the quantity required to complete the chemical change has to be added or the lime will be incompletely slaked, which, for some of the uses to which it is put would be a serious disadvantage. Imperfectly slaked lime would, for example, be unsuitable for making plaster for walls or ceilings, and in order to ensure complete hydration, the wet mixture—lime-putty—may be left for some weeks (at least a month), according to the lime from which it has been made.

In modern practice there is a tendency to use mechanical appliances for slaking, and the term " hydrated lime " is often used for the finely powdered product so produced, while that dealt with by hand is called slaked lime; these are, of course, terms of convenience, for slaked lime *is* hydrated lime, and vice-versa.

The result of mechanical hydration is to produce a dry powder, but there does not appear to be the same facility for control as in the older method; there is often a tendency for the material to become overheated, and, in consequence, the product loses to some extent its power of forming a plastic mixture with water, in which case a lime-putty or plaster made from it neither spreads nor adheres as well as hand-slaked lime, if used for walls and ceilings. This appears to be due to the fact that the plasticity of lime-putty arises from the presence of colloidal lime (see page 194) which is formed in larger quantity when the plaster is made by slaking quicklime than when water is added to the dry powdery mechanically-slaked material [8].

Since hydrated lime is convenient for nearly all the purposes for which ordinary lime is used and more convenient for many of them, and has moreover, the added advantage of being more easily stored and transported, careful attention is being paid to its better manufacture [9, 10].

Mortar.—Mortar is the pasty material, made by mixing slaked lime with sand and water, that is used in binding together the bricks or stones used in the process of building. On exposure to the air it sets or becomes hard, partly as a normal result of drying, and partly owing to the absorption by the lime of carbon dioxide from the air. The setting of mortar appears to depend upon the formation of a colloidal hydroxide of lime when the material is first wetted: as it dries the colloidal material " sets " after the fashion of glue, and, at a later stage in the process, calcium carbonate begins to form. The object of the sand is to make the material more porous and thus further the absorption of carbon dioxide, and it also lessens the amount of shrinkage that takes place as the mortar dries and sets [11].

The making of mortar and plaster was the subject of a communication to the Philosophical Society of Oxford in 1684, when Sir William Petty,

> "having thought it worth his while to enquire into ye proportion of ye materials, used in making severall sorts of Mortar, the following report was drawn up: The Mortar used by our Plaisterers is generally of two sorts, course or ffine: 1. *Course* mortar is made of Lime, sand, and hair: the Lime used here at Oxford is of 2 sorts, *viz.* Chalk-lime, made of chalk-stone dug at Nettlebed, and other places, and burnt: or 2dly Hard stone lime, which is made of hard rag stone, burnt: this last sort of lime is much stronger, and will go 2 yards square in five, farther, (for it takes up far greater quantity of sand, and water), than ye former, which is the finer of ye two, and ye more beautifull, and glorious, to the eye. In ye making of *fine* mortar mix one bushell of chalk lime with ½ a peck of hair, or a bushell of hard stone lime with a peck of hair, and as much water as is necessary. Course mortar is used next to ye lathing, or ye stone, or brick-wall; ffine mortar is drawn on ye other, and makes it white, and beautifull" [3].

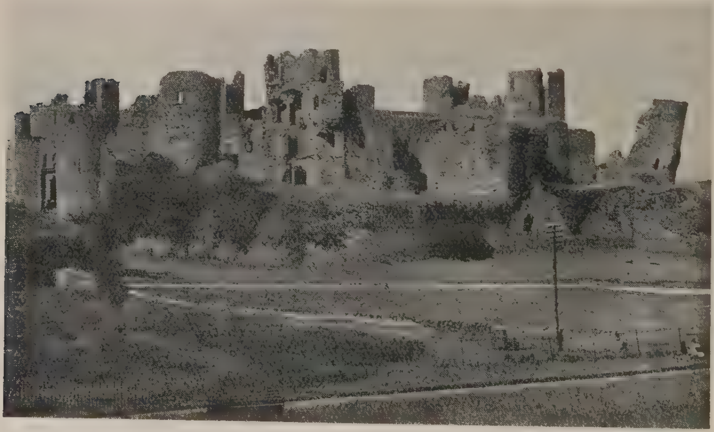

FIG. 223.—CAERPHILLY CASTLE, GLAMORGAN.

The quality of the mortar used in this 13th century building is such that although the outer wall of the damaged tower on the right overhangs its base it shows no signs of disintegration.

The excellent quality of the lime mortars made by the early builders of castles in this country is illustrated in the "leaning" tower of Caerphilly Castle in Glamorgan. The building was erected in the 13th century, and at some later date, probably in the 17th century, it was partly destroyed by means of gunpowder "mines." Some of the towers were demolished, but in one case, although the inner portion was shattered, the outer portion, which was thrown out of the perpendicular, remained standing;

the wall overhangs its base to the extent of nine feet, but the mortar holds the stones together so well that there is no tendency for them to fall away; *Fig.* 223.

Concrete.—Mixtures of stone and lime-mortar were used in building and construction before concrete, as we now understand the word, was made. The cores of Roman walls often consist of a jumbled mass of stones mixed with mortar, and similar usage prevailed throughout the centuries.

The foundations of Salisbury Cathedral (A.D. 1100) were made of a kind of concrete bound with lime mortar, and in 1770, when the foundations of Newgate Prison were being laid, and part of the wall had to be erected on a boggy patch which was the site of the ditch of the old London wall, cartloads of bricks and mortar were thrown in. In other cases, liquid mortar was poured in to fill the cracks between the stones that had already been tipped: this was done between the heads of the piles on which Waterloo Bridge was built in 1811.

Concrete was first applied to building processes about 1820/30. From an essay [12] that, in 1836, gained a prize from the Royal Institute of British Architects, we learn that a common mixture was 1 part of Dorking lime to 4-12 parts of Thames ballast, Kentish rubble, or broken granite; sometimes the ingredients were mixed together and slaked as mortar, or the ballast was placed in position and liquid mortar poured over it, or the space was filled with water, and lime and ballast, dry mixed, thrown in. A few years later Major-General Sir C. W. Pasley, Lecturer on Architecture at the Military School at Chatham, stated that the recently constructed sea wall at Brighton was the first application of concrete for other purposes than the making of foundations.

Many of the various kinds of *artificial stone* that have from time to time been introduced may be regarded as special forms of cement-concrete. For example, the so-called Granolithic paving stone is made by moulding a mixture of chips of igneous rock with Portland cement, and steeping in a solution of sodium silicate the slabs so produced. The sodium silicate assists in indurating the mixture and in filling up the spaces between the fragments of which it consists. In Leicestershire, also, cement made from the Lias Limestone, near Barrow, has been used in conjunction with the igneous rocks of Mountsorrel and Groby, and in other places similar use is made of the waste products of local quarries [22].

Cement. — Various attempts had been made to produce cements more effective than lime mortar, and available for purposes for which that material is not suitable : the so-called Roman Cement has already been mentioned (page 281), and in 1756 James Smeaton spent much time in trying to make an efficient hydraulic* cement for use in building the third Eddystone lighthouse [13]. He found, as we have already seen, that the impure limestone (Lias) of Watchet in Somerset was particularly suitable for his purpose, when burnt and mixed with pozzolana, a kind of volcanic sand.

Other experiments were conducted in this country and on the continent, and the most successful were those of Joseph Aspdin, a Leeds bricklayer, who in 1811 invented a cement to which he gave the name of Portland Cement; thirteen years later he took out a patent, and as its valuable properties became more widely recognised the new cement entirely revolutionised work in concrete, which, especially when used in conjunction with steel, has become one of our most important building media.

Aspdin's original cement, which was made by lightly burning a mixture of lime and clay, was quite different from the material now known as Portland Cement, which is made by subjecting a suitable mixture of those materials to a very high temperature, and was first produced by William Aspdin in 1848 [14 & 21].

In 1826 Sir C. W. Pasley made cement with properties similar to that of Joseph Aspdin by burning chalk and mud from the bed of the Medway, and for a time, the most important centre of the Portland Cement industry was situated in northern Kent.

Portland Cement is now made by heating a suitable mixture of calcareous and argillaceous materials sufficiently to cause partial fusion, and then grinding the product. The raw materials contain calcium carbonate and aluminium silicate, and the effect of the heating is to produce complex silicates of calcium and aluminium that possess the property of combining with water to produce a hard stone-like mass. Originally the cement was made by grinding the raw material with water to form a mixture (slurry) of the consistency of cream, which, after sifting, was allowed to stand in troughs until the solid matter had settled out. The clear water was drawn off and the damp pasty mass moulded into bricks which were first dried and then burned in kilns to a temperature of about 2,600°F., yielding greenish-grey cindery-looking masses of "clinker," that, when ground, constituted Portland Cement.

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* As used nowadays the term hydraulic limestone signifies one that contains enough silica and alumina to yield, when burnt, a cement or mortar that sets under water.

This process is almost obsolete although it is still carried out when the raw materials are soft, as in the case of chalk and river mud. When the original rocks are hard, as for example, the limestone and shales of the Liassic and Carboniferous Formations, a semi-dry process is now generally used. A suitable mixture of calcareous and clayey material is crushed, mixed, and ground with water until a *thick* " slurry " is formed which can be either made into bricks and burned, or pumped into a " rotary kiln." The rotary kiln is a large iron cylinder lined with fire-bricks, slightly inclined, and arranged so that it can be slowly rotated. The raw materials are fed into the upper end of the kiln and the heat is produced by the burning of finely pulverised coal injected at the lower end. The slurry, which dries in the upper end is chemically changed as it reaches the lower and hotter region, until finally, at the point of most intense combustion it is converted somewhat suddenly into hard greenish-black pellets of clinker. The pellets are cooled by being passed through a long revolving drum in a current of air, and, when suitably ground, like the clinker produced by the " wet process," they yield Portland Cement. The form of the kiln and the details of the process may be modified according to local conditions and to the nature of the raw materials that are available [23, 26].

Apart from its use in the manufacture of cementing materials limestone is extensively used as the " aggregate " of concrete, and although not favourably regarded by some authorities on account of its solubility, in the United States [15], limestone, including dolomite, is used for that purpose in greater quantity than any other stone and is found to be satisfactory.

Gypsum and alabaster.—Although not limestone, gypsum and alabaster call for a brief comment in the present work, because, like that rock, they are derived from calcareous salts present in natural waters, and some of their industrial applications resemble those of limestone. In this country gypsum occurs in Permian, Triassic, and Jurassic rocks. In the (Permian) Magnesian Limestone it is present near Penrith in Cumberland, and on the eastern side of the Pennines the localities in which it is found extend from Nottinghamshire to Durham. The distribution in the Trias is somewhat similar: it occurs near Whitehaven on the one hand, and in Nottinghamshire, Derbyshire, and Leicestershire on the other; farther south it occurs in Gloucestershire, Glamorgan and Somerset. The Permian and Triassic masses are of considerable commercial importance, but the occurrences in the Jurassic strata are not important; they are almost confined to the Purbeck Beds near Swanage and near Battle in Sussex. In the former locality, discontinuous masses occur in the Lower Purbeck Beds, and they have, from time to time, been collected for garden decoration [17]. The gypsum deposits in the Purbeck Beds of Sussex acquired fresh importance in connection with the borings put down during the investigation of the Wealden area with a view to ascertaining the occurrence and distribution of concealed Coal bearing strata, and in 1928 about 240 hands were employed in the winning and manufacture of the material, most of which is made into Plaster of Paris, Keene's Cement, mineral white, or manure. The supply is derived from lenticular masses and veins distributed throughout some 50 or 60 feet of strata, which are reached by means of deep shafts [17a].

After the close of Coal Measure times, dry, and even desert-like conditions prevailed, resulting in the formation of areas of sea water, isolated in consequence of earth movements, and of inland lakes in which (as in the case of the present Dead Sea) evaporation exceeded the supply. As the water dried up, the salts in solution were deposited, but although calcium carbonate is much less soluble than calcium sulphate [16], and it would be expected that the least soluble salts would be deposited first, we do not find in the Permian and Triassic rocks extensive deposits of calcium carbonate due to precipitation: gypsum occurs instead.

The probable explanation is that the Coal Measures, which were then undergoing denudation, contained appreciable amounts of sulphur combined with iron in the form of pyrites, which mineral, under the oxidising conditions prevailing in the post-Carboniferous deserts, gave rise to sulphuric acid; this, interacting with the calcium carbonate formed calcium sulphate, which, as the water dried up and the solution became more and more concentrated, was deposited as gypsum or alabaster. The gypsum occurs as beds varying from a few inches to several feet in thickness, as veins, or as isolated masses or nodules in the marls; *Fig.* 224.

It is found that calcium sulphate remains in solution in sea water until 80% of the water has been evaporated, but salt, on the other hand, is not deposited until 93% of the water has been evaporated, so that gypsum is more abundant and more widely spread than deposits of salt, although, owing to the much greater solubility of the latter substance, the deposits, where they occur are usually far more extensive than those consisting of gypsum.

The amount of gypsum that can be dissolved in water is so small that enormous quantities of water must have been evaporated in order to provide the material of the commercially important gypsum deposits. It has been calculated that the evaporation of the water in an ocean basin 1,000 feet deep would only produce 0.7 feet of gypsum, and since some gypsum beds are many feet in thickness they must represent the evaporation of more water than could have been present at any one time in the basin in which the deposit was laid down: in other words, the local conditions must have been such that fresh supplies of gypsum-bearing water constantly entered a basin of deposition, while evaporation continued over a very long period.

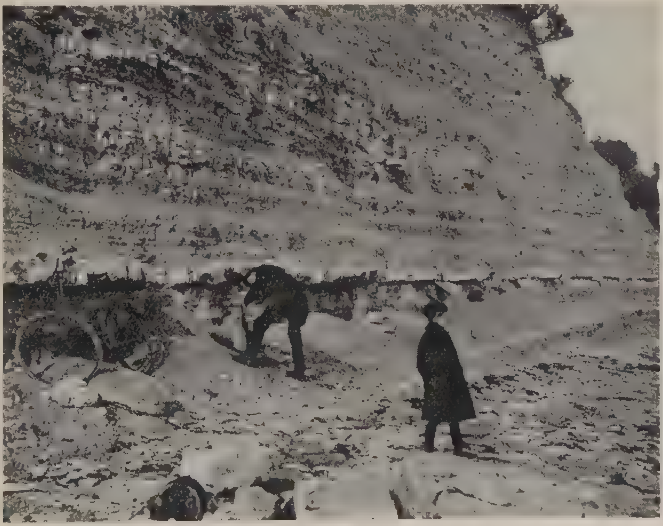

FIG. 224.—GYPSUM IN THE TRIASSIC MARLS.

Cliff-section at Penarth, Glamorgan, showing a band of gypsum (alabaster) in the marl of the Trias. (*Photo F.F.M.*)

In attempting to account for the existence of such conditions, we may take the case of the present Mediterranean Sea. The influx of fresh water from the rivers is insufficient to keep pace with the amount lost by evaporation, and the water level is maintained by additions from the Atlantic. If the amount of water so added were to diminish, concentration of the dissolved salts would increase, and eventually some of them would be deposited, gypsum being among the first. If, at that time, the conditions were such that the amount received from the Atlantic was just enough to maintain the necessary state of concentration, gypsum would continue to be deposited, although common salt would remain in solution. In this way a considerable thickness of gypsum might be laid down, representing the calcium sulphate held in solution by a volume of water much greater than the basin itself could have held at any one time had it been completely isolated.

As we have already seen, rock folding and uplift in post-Carboniferous times resulted in the isolation (partial or complete) of arms of the sea, and in the development of inland salt lakes where evaporation was greater than the supply from rivers, so that conditions such as those outlined might well have occurred from time to time and in a variety of places. At that time, also, the supply of gypsum was probably greater than usual, because the Carboniferous Limestone and the Coal Measures were undergoing denudation—the former supplying calcium carbonate and the latter sulphuric acid from the decomposition of pyrites, two substances, the interaction of which would produce calcium sulphate.

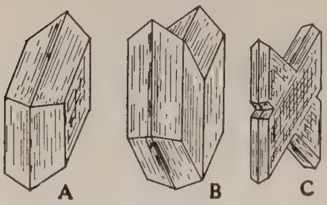

FIG. 225.—CRYSTALS OF GYPSUM.

Crystals of gypsum (Selenite) usually take the form of stout oblique prisms. A, a simple crystal of a common type, B and C, twinned crystals.

The crystals may be as much as four or five inches long, but are usually about half that size.

Gypsum is hydrated calcium sulphate; if pure, it is colourless and transparent, and if free to crystallise it assumes a characteristic shape (*Fig.* 225) as in the mineral known as *Selenite*. Sometimes, veins of gypsum consist of closely packed long slender crystals that give the mass a fibrous appearance (as in the variety *Satin Spar*), but large masses are usually aggregates of crystals that have interfered with one another's growth, giving rise to a rock with a saccharoidal or sugar-like appearance; this variety is known as alabaster. At one time, owing to its homogeneous nature and the ease with which it can be carved, for it is considerably softer than marble, alabaster was extensively used in ecclesiastical decoration, for statuary, effigies (*Fig.* 226) and small ornamental objects, but on account of its softness and solubility it is only suitable for internal work.

Alabaster for decorative work is still produced at Fauld in Staffordshire and Chellaston in Derbyshire (from rocks of Triassic age), and at a number of other places the nodules or the more easily accessible veins are worked for local use in rockeries and garden decoration [13]. In the lower part of the (Triassic) Green Marls at Penarth, near Cardiff, tabular masses and thin veins of gypsum occur (*Fig.* 224), the former, often pinkish in colour, have occasionally been worked, as for example, for wall-slabs in the corridors of University College, Cardiff.

Although less used as " alabaster " than hitherto, gypsum has many modern uses, such as, for example, the making of Plaster of Paris, cements of various kinds, " mineral white," fertilisers, and polishing materials; it is also in demand for improving the water used in brewing.

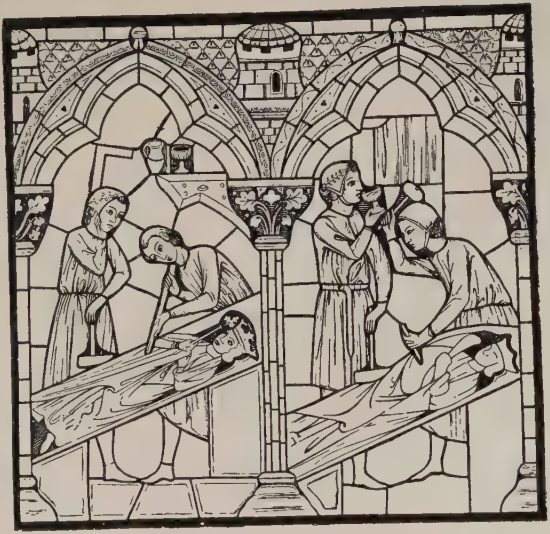

FIG. 226.—MEDIÆVAL SCULPTORS.

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Plaster of Paris.—Gypsum contains water; it is represented by the formula $CaSO_4, 2H_2O$, and when the material is heated, part of the water is driven off leaving a product that is capable of recombining with water, and setting into a hard mass. Plaster of Paris is gypsum from which about two-thirds of the water has been driven off by heat, and if the temperature is raised much above the point (392°F.) at which *all* the water is driven off, the product loses its setting properties and is said to be " overburnt."

Plaster of Paris is so called because it was first made from gypsum quarried in the hill of Montmartre, near Paris, and it is by no means a recent discovery.

It used to be prepared by the process known as " baking." The gypsum was broken into small pieces, heated in an oven and the product subsequently ground, but in modern practice it is usually prepared by " boiling," for which purpose the raw material is ground and the powder heated by means of flues in the floor of the firebrick pan or " kettle " in which it is placed. The kettle is a cylindrical vessel from 6 to 10 feet in depth and from 8 to 14 feet in diameter, and the material within it is agitated by means of revolving stirrers.

At about 212°F., steam is driven off and the material begins to run almost like water, while the escape of steam gives it the appearance of boiling, to which circumstance the process owes its name. When sufficient water has been driven off and the temperature is in the neighbourhood of 240°F., the charge loses its apparent liquidity and is run off into hoppers and stored in sacks. For certain purposes the plaster may, instead of being withdrawn at this stage be further heated; at about 270° a second " boiling " takes place and the material is discharged after reaching a temperature of 350° [20]; see Additional Note, page 455.

Plaster prepared by " boiling " takes two or three times longer to set than that prepared by " baking," probably because the latter contains a greater proportion of very fine particles.

Apart from its application in the finishing and decorating of buildings, Plaster of Paris has many other uses; it is necessary in dentistry, in lithography, and in making moulds and casts for various purposes. Its value in the preparation of casts is due to the fact that the process of setting is accompanied by slight expansion, so that the details of the mould are sharply reproduced.

Among the special kinds of cement made from gypsum may be mentioned Keene's Cement (which consists of Plaster of Paris soaked in alum-water, re-burnt, and ground), and Parian Cement (which differs from Keene's in that borax is used instead of alum). Ground gypsum is also added during the making of portland cement when it is desired to control the rate of setting—gypsum exercises a retarding effect.

Gypsum in industry. — Gypsum has other uses than as a medium for carving and as the raw material of Plaster of Paris. *Mineral white*, or *terra alba*, is made by the careful grinding of suitable pure varieties; the material is crushed, ground between millstones, and re-ground after sifting through fine silk-lawn, until it is in the condition of an impalpable powder. It is used as a “filler” in producing a smooth surface in high grades of paper, and, mixed with starch, it gives a “finish” to cheap cotton and lace goods; it also figures in the manufacture of paint, such as venetian red.

In agriculture, gypsum (under the name of land-plaster) affords a convenient means of supplying sulphates to the soil, and it assists in rendering available any potash that may be present in the rock fragments or mineral grains of which the soil consists, but, owing to the increased use of “superphosphates,” gypsum is not largely used as a fertiliser in this country; it is, however, employed by hop growers, and, mixed with manure that is being stored, it tends to prevent loss of ammonia.

In the brewing industry gypsum is used to impart “permanent” hardness to soft waters. Moderately hard water is desirable in brewing, and while at Burton-on-Trent and other places suitable water occurs naturally, elsewhere gypsum is added to the local water.

Marl, full of gypsum veins that are too small to be separated, is ground and used in polishing “tin-plates”—the tinned-iron sheets for can- and box-making that are made extensively in South Wales.

A variety of calcium sulphate without combined water is the mineral Anhydrite, which is harder and relatively heavier than gypsum. It naturally takes up water and gives rise to gypsum, and it is believed that in many cases the deposits of that mineral were originally formed as anhydrite. Anhydrite is undesirable in gypsum that is to be converted into Plaster of Paris, because it is equivalent to so much dead-burnt plaster and retards the setting.

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CHAPTER XVII.

LIMESTONE ON THE ROAD AND IN THE FURNACE.

> "The Road is one of the great fundamental institutions of mankind. . . . It . . . determines the sites of many cities and the growth and nourishment of all. . . . It is the channel of all trade, and, what is more important, of all ideas. It . . . is a sustenance without which organised society would be impossible."
>
> HILAIRE BELLOC, in "*The Stane Street*" (1924).

Limestone in roadmaking.—At the present time the making and mending of roads consumes about one-third of the total limestone output of this country, most of the rock being derived from the Devonian and Carboniferous Systems, and from the harder limestones that occasionally occur among the Jurassic strata. The extensive use of stone for roadmaking is, however, a comparatively recent innovation.

Prior to the coming of the Romans hardly any roads (as we understand the term) existed in this country at all, for the inhabitants—few in number and simple in their wants—were content with the tracks made by the passage to and fro of men and animals, and there were large areas of forest and marshland that were quite impassable.

To the Romans, the quick and safe transport of large bodies of men was a prime necessity, and the network of roads they made showed considerable surveying and engineering skill [1]. The made-road usually consisted of several layers and was often as much as 54 inches in thickness: on a foundation of two courses of flat stones and mortar was placed a layer of broken stone mixed with lime, followed by a layer of broken bricks, pots, and lime, and the surface was a pavement of irregular stones, closely and evenly packed. The details naturally vary from place to place according to the nature of the material that was available; for example, a section of the Watling street (exposed during some excavations in Rochester) was about 7 feet below the modern road level, and comprised the following layers, commencing with the lowest—angular gravel, flints, angular gravel, rammed chalk, flints packed with sand and earth for the surface [2].

The main object of the Roman road was to provide a means of quick transport from place to place; the Saxon villages, on the other hand, usually grew up near streams and were off the main highways, with the result that after the departure of the Romans, their roads were neglected and soon fell into disrepair; by the Middle Ages some of them had even been encroached upon by woods and sections were completely lost.

From that time until well into the 18th century very little serious work was done, either in the way of making new roads or in maintaining those that already existed, although in London and other large cities the streets were paved with boulders and large pebbles, often brought from the coast.

Many contemporary writers make reference to the deplorable state of the roads between the 16th and the 18th centuries. In the Weald, where there were extensive iron works, traffic to and from the furnaces naturally did much damage to the already indifferent roads, and an order was made to the effect that

> "the occupiers of all maner of iron works . . . which shall at any time hereafter carie . . . any coles, mine* or iron to or from anie of their iron works between the twelfe daie of October, and the first daie of maie, yeerlie (shall in proportion to the amount of traffic involved) cause also to be carried . . . stone sand or chalk, meet for the repairing and amending of the said high waies" [3].

Two centuries later the roads in the same region suffered much from the traffic of timber to the shipbuilding yards at the mouth of the Thames. From "*England Displayed: Travels by a Society of Gentlemen,*" edited by F. Russell, 1769 (Vol. 1, 116), we learn that

> "The roads in the winter season are the worst in England, for many of the prodigious trees which grow here and are carried thro' this part of the country in the summer time . . . on a carriage . . . drawn by twenty oxen, advance so slowly that it is often several years before the tree reaches the place of its destination, for if the rain sets in it stirs no more for that year."

Such references are by no means uncommon, but one other, this time relating to the North of England, must suffice—Arthur Young, who was for a time Secretary to the Board of Agriculture, and a great traveller, in "*A Six Months' Tour through the North of England*" (1770) wrote of the roads to Wigan:—

> "I know not, in the whole range of language, terms sufficiently expressive to describe this infernal road . . . travellers . . . will here meet with ruts which I actually measured 4 feet deep, and floating with mud only from a wet summer."

Towards the end of the 17th century there was a marked increase in wheeled traffic, but roads that were passable for men on horseback were quite unsuited for vehicular transport, and to this, no doubt, are due in large measure the complaints such as those just instanced. The turnpike road belongs to this transitional period; under it, separate sections of road were maintained by private persons or by companies who had the right of exacting toll from those who used it.

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* At one time the word "mine" referred to what we now call ore, and not to the place from which the ore was obtained. The old meaning of the word is seen in names such as "Black Pins Mine" applied to the ironstones that occur in the north-eastern region of the South Wales coalfield.

The result of this demand for better roads was that the early part of last century saw the commencement of a new era in roadmaking, and at the present time developments in that direction are proceeding more rapidly than ever. This is illustrated by the following details concerning the output from quarries in this country. Of 31,003,000 tons of stone of all kinds (the total output for 1927) 15,965,000 tons were for roadmaking, and of that amount 5,027,000 tons were limestone. There has, within the last few years, been a considerable increase in the importance of limestone for roadmaking as the following table indicates :—

	1913	1927
Total stone quarried for all purposes	23,816,460	31,003,000
Limestone quarried for all purposes	12,740,664	14,411,000
Limestone for roadmaking ...	1,110,000*	5,027,000

The reason for the increase in the proportion of the stone output used for road-making is, of course, the increase in the construction and improvement of roads, but the reason for the very great advance in the utilisation of limestone will be best appreciated after a brief reference to the properties desirable in a roadstone and to modern practice in road-making [4].

Stones for use as road-metal must be hard enough to resist the crushing, and tough enough to withstand the abrasion to which they will be subjected, and a further desirable character is that the powder produced as the rock is worn shall form a cementing material tending to the closer binding of the whole; in addition, for many roads, it is necessary that the rock and its powder shall mix well with tar, bitumen, or similar material.

Laboratory tests and practical experience show that although limestones are neither as tough nor as hard as many other rocks that are used in road-making, they " have other advantages as roadstones, such as cementing qualities, and the ease with which they form a good aggregate with bituminous binders " [5]. We find, therefore, that road-making developments have tended to a steady increase in the use of limestone and dolomite.

---

* This is the figure for 1907, that for 1913 I have not been able to ascertain.

Paved roads, such as those frequently made by the Romans, were not suitable for wheeled traffic owing to the tendency of the slabs to settle irregularly, and at the beginning of the present era of road-making, granite " setts " or small boulders of igneous rock were very extensively used, because, in addition to being hard, granite does not tend to grow slippery with wear, owing to the fact that, of the constituent minerals, the felspar breaks and decomposes more readily than the quartz, so that as the rock disintegrates the surface remains rough.

The system of road-making introduced in 1816 by John Loudon McAdam made use of what were, in this country, new principles. McAdam, who was born in Ayr in 1756, was really a McGregor, but when his family settled in the south of Scotland it assumed the name McAdam. As a pioneer in road-making he was contemporary with Thomas Telford (who was appointed in 1810 to build the Holyhead Road in order to expedite postal communication with Ireland) and while employed in various capacities (he was appointed Surveyor General of the Bristol Road in 1815) McAdam had opportunities of developing his ideas, and although the kind of road he advocated differs vastly from the macadam road of to-day, his work undoubtedly led to the development of the network of coach roads that, in the early part of last century, facilitated transport in a manner previously unknown, and thus, by fostering commercial intercourse, contributed much to the prosperity of the nation. It can hardly be said that McAdam invented the broken-stone road, for similar methods had already been employed on the continent; what he did was to advocate and apply the principle in this country.

Although opposed in some quarters, his methods were widely adopted, and " macadam " soon became a recognised everyday word. In 1839, Murchison, discussing the distribution of boulders of igneous rock distributed by the agency of ice during the glacial period, remarked that such boulders were " fast disappearing through the labours of the macadamites " [6], and, in the same year, Phillip James Bailey used the expression " macadamise the world " in his " Festus "—a version of the theme of the " Faust " legend which, although long and tedious, was enthusiastically received and ran through eleven editions, in the last of which it had grown to over 40,000 lines.

McAdam's original practice was to use broken stone; the fragments were roughly cuboidal in shape, none weighing above six ounces; they were put down in three layers, two of which were of the larger stones, while the third or surface layer consisted of one-inch chips, and the entire thickness was about 10 inches. He did not use any binding material other than mud, but relied upon the pressure and abrasion due to traffic to produce a layer as hard and as durable as the stone from which it was made. He preferred granite or "greenstone," both igneous rocks, and considered that if suitable material were well laid, but little attention need be paid to the foundations of the road. He obtained his "camber" by shaping the foundation so that the thickness of the broken stone layer was practically uniform from side to side.

Telford's system differed from that of McAdam in that the stone was laid on a flat foundation—the camber being obtained by using (in the lowest layer) larger stones in the middle of the road than at the sides. The stones of the first layer were carefully packed and the surface made even, after which two layers of broken stone were put down, with an interval of time between, sufficient to allow the first layer to become more or less consolidated by traffic [7].

Modern practice, although the same in principle, differs from those of McAdam and Telford in many important respects, especially in the steps that are taken to secure a good foundation, in the introduction of some form of binding material to assist in rendering the surface layers compact, and in the employment of a steam-roller to effect consolidation before traffic is allowed upon the road.

So long as macadam roads were water-bound—that is to say, water was used to assist in the formation of the cementing material—igneous rocks were most extensively used, but the rise and rapid growth of motor traffic and the demand for a road surface as free as possible from noise and dust, led to the adoption of a modified macadam road, in which tar or some other bituminous material was used to bind the fragments together. For this purpose, the crushed stone, dried and suitably heated, is thoroughly mixed with tar, and the material, when spread upon the road and rolled, soon provides a relatively even, durable, water-proof surface.

Since it is necessary for the tar to adhere perfectly to the stone, granite* is not considered to be suitable for tar-macadam because, if strongly heated, some of the minerals tend to disintegrate, thus making the rock friable, and unless the heating has been sufficient the tar will not adhere properly. Although granite is not suitable, some of the finer grained igneous rocks and some sandstones make good tar-macadam, but the great increase in the use of limestone in road-making since the beginning of the present century is largely due to the ease with which it can be mixed with tar, and the excellence of the road surface it then provides.

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* Using the term in its strict scientific sense, that is, for a rock consisting of the minerals quartz, felspar, and mica (or similar minerals) in moderately large crystals; for trade purposes "granite" is made to include many other kinds of rock, a practice that is to be deprecated.

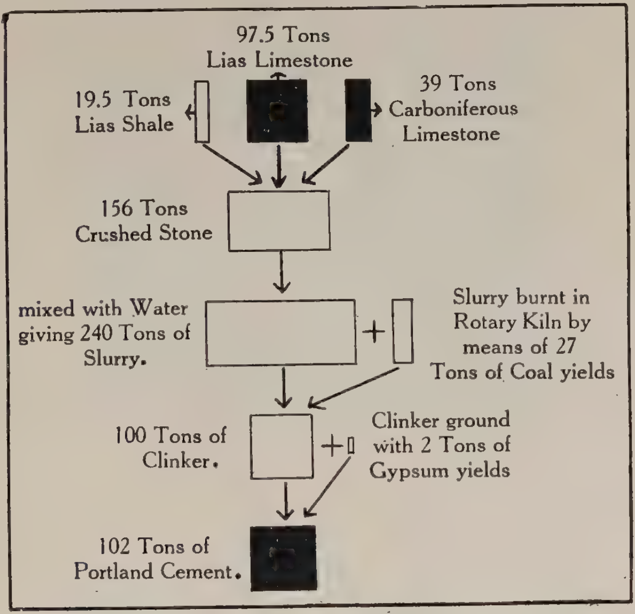
97.5 Tons
Lias Limestone
19.5 Tons
Lias Shale
39 Tons
Carboniferous
Limestone
156 Tons
Crushed Stone
mixed with Water
giving 240 Tons of
Slurry.
+
Slurry burnt in
Rotary Kiln by
means of 27
Tons of Coal yields
100 Tons of
Clinker.
+
Clinker ground
with 2 Tons of
Gypsum yields
102 Tons of
Portland Cement.

FIG. 227.—DIAGRAM ILLUSTRATING THE USE OF LIMESTONE IN CEMENT MAKING.

The diagram is based upon the process in a large works using limestone and shale from the Lower Lias.

The introduction of asphalt roads also led to an increased demand for limestone, for not only is much of the "asphalt" a highly bituminous limestone, but limestone dust is an important ingredient in the mixture that is spread upon the road; the material has, moreover, to be laid down on an even unyielding surface, in the attainment of which Portland Cement plays an important part, and the manufacture of a ton of Portland Cement involves the use of more than that amount of limestone (*Fig.* 227).

Although its widespread adoption is a comparatively recent development, asphalt paving was introduced in Paris in 1854, and Threadneedle Street, in London, was paved by the Val de Travers Company in 1869.

Considered as a class, limestones are softer than most of the other rocks used for road-making and many of them are quite unsuitable for the purpose; in many cases, however, the disadvantages arising from inferior hardness are more than outbalanced by some of the other properties to which reference has already been made. The best varieties are those with a mixed assemblage of small fossil remains, such as foraminifera or broken shells (*Fig.* 228), and especially those which are somewhat bituminous, as is the case with many parts of the Carboniferous Limestone. Limestones with large fossil shells or with large crinoidal fragments (*Fig.* 229) are not usually suitable, because the fossils

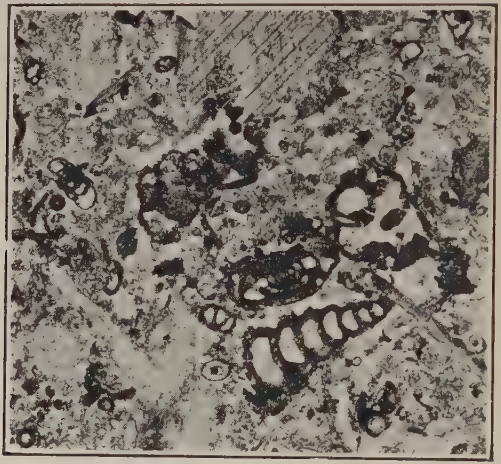

FIG. 228.—PHOTOMICROGRAPH OF A THIN SECTION OF LIMESTONE.

Carboniferous Limestone ("Mendip" Limestone) from Winford, near Bristol, consisting largely of foraminiferal shells and fragments of the shells of other marine organisms, cemented together by granular and crystalline calcite; magnified about 25 diameters. (Reproduced by permission of the Director of the Geological Survey.)

consist of the mineral calcite, in which the cleavage is usually well developed, so that the rock fractures readily; if the crinoid stems are much broken and the fragments small, the brittleness of the rock is considerably reduced. Fine grained dolomites or dolomitic limestones, especially those with an even texture and closely interlocking crystals, usually make good roadstones, because the rock is generally harder than limestone, and, during the progress of the dolomitisation the whole mass, including the fossils, has often been rendered uniformly and finely crystalline, with a resulting increase in toughness.

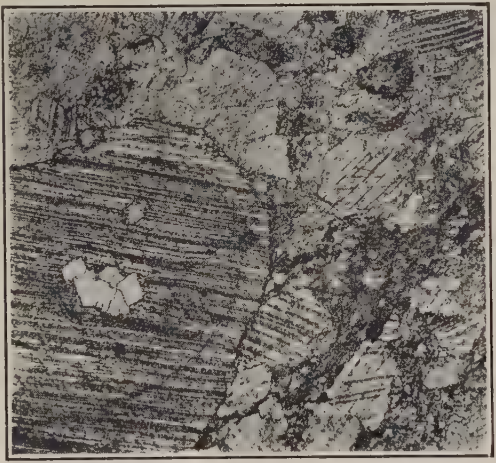

FIG. 229.—PHOTOMICROGRAPH OF A THIN SECTION OF LIMESTONE.

Devonian Limestone from Barton, St. Marychurch, Devonshire, consisting largely of crystalline calcite representing fragments of the stems of crinoids. The largest fragment of calcite shows evidence of the characteristic lamellar or platy twinning of the crystals, and includes a few rhombohedral crystals of dolomite; magnified about 25 diameters. (Reproduced by permission of the Director of the Geological Survey.)

Only by laboratory tests, correlated with observations when in use, can the suitability or otherwise of a limestone (or indeed, any other stone) for road-making, be determined, although the examination of thin sections under the microscope often yields valuable information. There are many instances of stones being chosen or rejected on appearance only, using properties such as colour as criteria, and such methods are likely to prove either expensive to the user, who may thus get unsuitable material, or unfair to the dealer, whose stone, although good, is not purchased. In the case of a large quarry in South Wales, for example, local road makers refused to take portions of the stone (a fine grained dolomitic limestone) because it was, in patches, brownish in colour, but accepted rock that was black, although the quarrymen knew from experience that the stone they could not sell was the toughest in the quarry !

An instance of the danger of basing conclusions upon an insufficient knowledge of the technique of road-making is afforded by the report of a committee of the National Horse Association that enquired (1929) into the causes of slippery roads. The Committee expressed the opinion that slipperiness was due to the use of limestone in the surface coat, whereas it is claimed by those experienced in road-making that slipperiness results not from the stone, but from the nature of the material used for binding and from the method of finishing the surface [8].

As with building stones, there are convenient tests that may be applied to stones it is proposed to use for road-making, such as, for example, those devised by E. J. Lovegrove and described in a recent memoir of the Geological Survey [5]. The resistance to attrition is determined by rotating a definite number of pieces of stone in an iron cylinder at a known rate and for a standard period of time, and ascertaining the percentage of the whole quantity of stone that will, at the end of the test, pass through a sieve with spaces one-sixteenth of an inch in diameter. The effects of abrasion can be determined by means of a revolving iron plate, and the toughness by noting the height through which a hammer of a certain weight must fall in order to break a unit mass of the stone; see Additional Note, page 449.

Limestone for metallurgical use.—The value of limestone as a flux—that is, as a means of facilitating the extraction of metals, such as iron, from their ores—has long been recognised, and the rock has always been dug for the purpose in the neighbourhood of iron and steel works, as for example, near Dudley (page 102). When John Guest began, in the middle of the 18th century, to mine coal around Merthyr Tydfil, the farmers brought to the steel works lime that had been burnt locally, and the customary rate of exchange was a halfpenny and a sack of lime in return for a sack of coal.

At the present time 31 per cent. of the total limestone output of this country is used in blast furnaces, and its importance in the metallurgical industries can be realised from the fact that something like half a ton of limestone is required in the manufacture of one ton of iron. The limestone is placed in the furnace with the ore and the fuel, and its principal function is to unite with the earthy constituents of the ore, such as silica and clay, to form the " slag " which floats on the molten iron, and can be drawn off separately. For metallurgical purposes a reasonably pure limestone is needed, because the more sandy or clayey material the limestone contains, the less lime there is available to combine with the earthy portion of the ore. The limestone also assists in removing the sulphur that may be present in the ore or in the fuel—an important factor, because sulphur is an undesirable impurity in iron and steel : metallurgical limestone has, therefore, to be free from minerals, such as pyrites, which contain sulphur.

Other properties such as an ability to withstand the crushing effect due to the weight of the material with which the furnace is charged, are also of importance, and only certain kinds of limestone are suitable for metallurgical purposes [9].

Practically all the metallurgical limestone used in this country is derived from the Carboniferous Limestone, while the magnesium-bearing or dolomitic varieties of limestone are a source of material for use in lining the " converters " and open-hearth furnaces in which iron is converted into steel.

The dolomite rock is burnt in upright kilns or furnaces, and yields a dense hard material which is ground until the fragments are about as large as peas ; tar is then added to assist in binding the material, which is rammed in place during the construction of the hearth of the furnace. The function of the dolomite, as in the case of the lime in a blast-furnace charge, is to assist in the removal of impurities (such as silica, phosphorus, and sulphur), which may be present in the crude iron.

Lime is also needed in the manufacture of the " silica bricks " that are used in furnace-construction because they are capable of withstanding high temperatures. It is added to the crushed silica-stone as " milk of lime " or as powdered slaked lime, or in both forms, to the extent of from 1.5 per cent. to 3 per cent., and not only does it assist in binding the raw material together during the process of firing, but the lime and any alkalies that may be present in the mixture combine with some of the silica to form fusible silicates that adhere to the less fusible particles, uniting them into a strong mass. It also plays a part in the physical changes which the silica undergoes as it is heated—changes that influence the ultimate strength and durability of the brick [10-12].

The demand for metallurgical limestone is determined by the prosperity of the coal and steel industries to a greater extent than is the case with most of the other purposes for which the rock is used: for example, for some years previous to 1920 the average annual output (Great Britain) for all purposes had been over eleven million tons; in 1921, after the disastrous coal strike that began in the previous October, the output fell to less than seven and a quarter million tons. The decrease was entirely due to the inactivity of the blast furnaces because the demand for road-making, cement-making, and lime-burning was practically the same as in previous years. It was not until 1923 that the output of limestone again rose above eleven million tons.

Limestone in the chemical industries and glassmaking. — Although the amount is small in comparison with the quantities used on roads and in blast furnaces, the chemical industries and glass works of this country are responsible for the consumption of considerably over a million tons of limestone per annum.

Limestone or lime is essential in the preparation of potash and soda, which are the basic ingredients of many important chemical manufacturing processes, such as the making of soap, chemicals, sugar, glycerine, dyes, oils, candles, disinfectants, bleaching powder, ammonia, cellulose, vulcanised rubber, insect-killing mixtures and artificial manures, and also in the mercerising of cotton goods and in the manufacture of artificial silk. Lime and whiting are essential ingredients in many kinds of water paint, and washable distemper; in many of them the " body " consists to a large extent of lime or whiting, and the cementing material is casein, which, on exposure to the air, forms with the lime an insoluble calcium caseinate.

In 1927, 33,000 tons of limestone were used in glass-making, either as ground rock (if sufficiently pure), as whiting, or as lime; glass is essentially a fused mixture of sand (silica), calcium carbonate, sodium or potassium carbonate, and oxide of lead. The proportions naturally vary according to the kind of glass that is being made, and other materials are used in making glass for special purposes.

It is impossible in the space available here to give details concerning the part played by the limestone or by lime in all the processes enumerated, and one example (its use in the purification of coal gas) which is given more on account of its interest than because it creates a great demand for lime, will suffice to illustrate the manner in which use is made of the chemical activities of lime.

Coal gas, when first liberated, contains, among other impurities, sulphur compounds, and these, on burning, yield sulphur dioxide, the emission of which into the atmosphere is objectionable. One of the processes in the purification of gas aims at removing the sulphur compounds by passing the gas through a series of rectangular iron tanks containing slaked lime, slightly damp, and spread on horizontal shelves. The lime combines with the sulphur compounds, and also with any carbon dioxide that may be present, forming a mixture of calcium sulphide and calcium carbonate; when no free lime remains the resulting product is called gas-lime or spent-lime.

Although the principle involved is not the same, it may be of interest to mention here some observations made by Dr. Plot, who was Professor of Chemistry at Oxford and Keeper of the Ashmolean Museum in the time of Charles II., concerning the noxious gases sometimes encountered in wells. In his "*Natural History of Oxfordshire,*" he wrote :—

> "Let all the *workmen* and such as upon any account whatever have occasion to dig or go down in these wells, first throw down into them a peck of good *Lime*, which slaking in the water, and fuming out at the top, will so effectually dispel all such poisonous vapours, that they may safely go down, and stay some time unhurt."

It has long been known that dry quicklime has germicidal properties, on which account it was customary to bury in quicklime the bodies of plague and cholera victims, and for the same reason, farm buildings, outhouses and walls and even cottages are, in many districts, frequently given a coat of lime-wash; this is particularly the case in South Wales: recent investigations, however, suggest that the disinfecting power of lime is less than was formerly supposed.

Lime figures largely in medical preparations, its application ranging from the use of lime water in the treatment of sour stomachs and to counteract acidity in food, to the use of lime dust in the treatment of tuberculosis [14].

For medicinal purposes, *Lime Water* is made by shaking washed slaked lime with 100 times its weight of distilled water and siphoning off the clear liquid, which should be stored in green glass bottles. *Lime Syrup* (Liquor Calcis Saccharata) is the clear liquid decanted off after slaked lime has been shaken with twice its weight of sugar and twenty times its weight of water. *Carron oil,* for application to burns and scalds, is a mixture containing equal quantities of lime water and linseed oil, while *Linimentum Calcis* is a mixture of lime water and olive oil.

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CHAPTER XVIII.

CONCLUSION.

> "In order to understand any matter, especially if we have to understand it for a practical end, we must begin by thinking out why and how it has come into existence, what its function is, and how it can best fulfil that function. Next we must note its effect once it is formed, and the results of the fulfilment of its function."
>
> HILAIRE BELLOC, in "*The Stane Street*" (1924).

The abundance of limestone in the British Isles.—Our discussion concerning the origin, distribution, and uses of limestone has necessitated enquiries into many branches of research, and it is hoped that the insertion of references to the appropriate literature will prove of assistance to those who desire more information than could be given in a work of this kind.

The importance of the part played by calcium carbonate in the realm of nature can hardly be over-estimated. It is necessary for the growth and reproduction of plants and animals, and it is an important member of the burden of inorganic materials carried in solution in the water of springs and rivers. Some of the calcium carbonate so dissolved is deposited as travertine or tufa, as stalagmite or stalactite, or reappears in the solid state as a result of the activities of aquatic plants and molluscs, but some is carried to the sea. Here, also, some is deposited by chemical action or by precipitation, but a much greater proportion is incorporated into the skeletal frames or coverings of marine animals, forming material that eventually mingles with, or may even constitute the bulk of the deposits that accumulate upon the sea floor.

Such deposits, formed during past periods of the earth's history and uplifted to become dry land, have given rise to limestone, to sandstone, or to clay, according to the material of which they consisted and the conditions under which they were deposited, and they have thus provided the materials for the continuation of the cycle—the solution of calcium carbonate, its "fixation" by animals and plants, and its subsequent re-deposition; for as Swinburne has put it, while

"The sea gives her shells to the shingle,
The earth gives her streams to the sea."

Finally, the importance of limestone in the past development and present condition of our country's economic position may again be emphasised.

The relative abundance of limestone in the British Isles is well illustrated in the Table of Strata (*Fig.* 230) and the maps that constitute *Figs.* 43, 46, 53, 58, 62, 65, 82, 96, and 133; and it is also indicated by the fact that only three English counties (Buckingham, Chester, and Huntingdon), three Welsh counties (Cardigan, Merioneth, and Montgomery), and five Irish counties (Galway, Kildare, Londonderry, Louth and Wicklow), do not appear in the Mines Department's records as producers of limestone or chalk, while in Scotland, two-thirds of the counties south of the Grampian Mountains produce limestone. North of that range the output (from Sutherlandshire only) is negligible, although limestone occurs among the Cambrian and Pre-Cambrian rocks of the North-west Highlands and the Western Isles, but owing to its remoteness from centres of population and industry it is not now worked.

The economic importance of this circumstance is incalculable, for there is scarcely a phase of modern life in which limestone does not play, directly or indirectly, a prominent part. In a country where there is no calcareous rock to determine the nature of the soil or to provide the means for its improvement, and no limestone that can be used for constructing buildings, for making mortar and cement, for metallurgical processes, or in chemical industries, the progress of civilisation must of necessity be slow and industrial developments unimportant; and the pre-eminence of our own country is to a large extent due to the abundance and wide distribution of a commodity that is not only indispensable in itself, but without which other natural resources could not be utilised to advantage. In contrast, we may take the case of the Falkland Islands, important as a sheep rearing region; there, owing to the complete absence of calcareous rocks, all the lime that is necessary for the conditioning of the soil has to be imported, at very great cost, and even the bones of dead animals are gathered, and ground or burnt, as being too valuable to waste.

The natural association of useful materials in the earth's crust.—A matter of more than passing interest in this connection is the wide distribution of limestone in the British Isles and its frequent association with other commodities in the manufacture of which it plays an important part. The influence of the *distribution* of limestone upon water supply, and upon agriculture (both direct in the part it has played in determining the nature of the soil, and indirect in the means it affords of making good the loss of lime

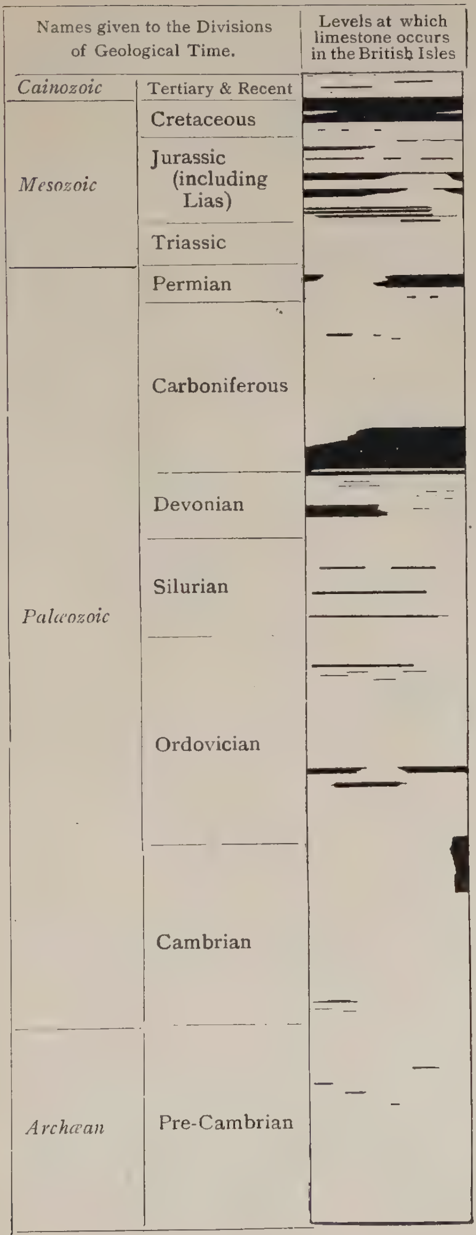
Names given to the Divisions of Geological Time.
Levels at which limestone occurs in the British Isles
Cainozoic
Tertiary & Recent
Cretaceous
Mesozoic
Jurassic (including Lias)
Triassic
Permian
Carboniferous
Devonian
Palæozoic
Silurian
Ordovician
Cambrian
Archæan
Pre-Cambrian

FIG. 230. — TABLE ILLUSTRATING THE GEOLOGICAL DISTRIBUTION OF LIMESTONES AND CALCAREOUS ROCKS IN GREAT BRITAIN AND IRELAND.

The relative thickness and continuity of the limestones and calcareous deposits are indicated diagrammatically by the blackened portions of the third column.

due to cultivation) has already been indicated, and the part it has played in these connections in determining the settlements of man and the progress of civilisation in this country can hardly be over-estimated. The effect of its *associations* are seen in the rise and development of many of the industries to which the pre-eminence of this country is due.

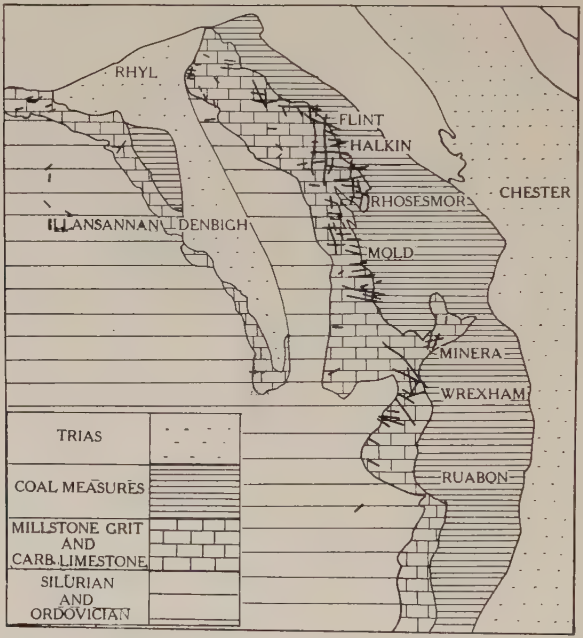
RHYL
FLINT
HALKIN
RHOSESMOR
CHESTER
LLANSANNAN
DENBIGH
MOLD
MINERA
WREXHAM
RUABON
TRIAS
COAL MEASURES
MILLSTONE GRIT AND CARB. LIMESTONE
SILURIAN AND ORDOVICIAN

FIG. 231.—The distribution of lead- and zinc-bearing veins in North Wales.

Map illustrating the occurrence of veins containing lead- and zinc-bearing minerals in the Carboniferous Limestone of North Wales, especially near its junction with the overlying shaly deposits of the Coal Measures.

Having been the foundation upon which the coal-bearing strata were laid down, the Carboniferous Limestone normally outcrops in association with the Coal Measures, and since the latter frequently contain ores of iron as well as coal, the location of many of the present iron- and steel-making centres has been due to the close association of the three essential ingredients for such industries—iron ore, coal for fuel, and limestone for flux; when the process of smelting had evolved to the extent of erecting furnaces in which the temperatures reached were such that ordinary bricks could not withstand the heat without softening, and heat resisting bricks were needed, the associated Coal Measure and Millstone Grit Formations provided the fireclay and the silica, and the Carboniferous Limestone the lime and the dolomite for that purpose.

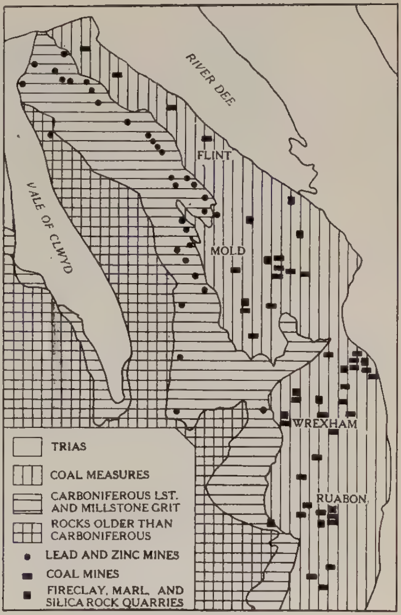
RIVER DEE
FLINT
VALE OF CLWYD
MOLD
WREXHAM
RUABON
TRIAS
COAL MEASURES
CARBONIFEROUS LST. AND MILLSTONE GRIT
ROCKS OLDER THAN CARBONIFEROUS
● LEAD AND ZINC MINES
▬ COAL MINES
■ FIRECLAY, MARL, AND SILICA ROCK QUARRIES

FIG. 232.—THE DISTRIBUTION OF USEFUL COMMODITIES IN THE CARBONIFEROUS ROCKS OF NORTH WALES.

It will be noticed that the coal-bearing strata are intimately associated with rocks in which occur lead and zinc, that were formerly of great importance, and with rocks containing clay, fireclay, silica, and limestone, that are essential in many modern industries.

In South Wales, for example, it was the close association of fuel, iron-ore, and limestone in the north-eastern corner of the coalfield between Pontypool and Merthyr that initiated industrial development in that area in the fifteenth and sixteenth centuries. The fuels used were wood and charcoal, of which there was an abundance, because at that time the district had not been denuded of its trees, but so enormous was the consumption of wood that by the middle of the eighteenth century the supply was practically exhausted, not only in South Wales, but also in other areas where iron works were situated, as for example, the Weald. The further consumption of wood in furnaces was at first discouraged and finally prohibited by Parliament, and serious attempts were made to use coal in the iron furnaces. For a long time these attempts were unsuccessful, but when a suitable process had been devised the industry continued in the regions in which it had already been established because the new fuel was also availab there. In South Wales and Staffordshire the ores used were th clay iron-stones of the Coal Measures, but in the middle of tl nineteenth century the exploitation of the low-grade but easil worked iron ores among the Jurassic strata—the altered oolit limestones to which reference has already been made—an

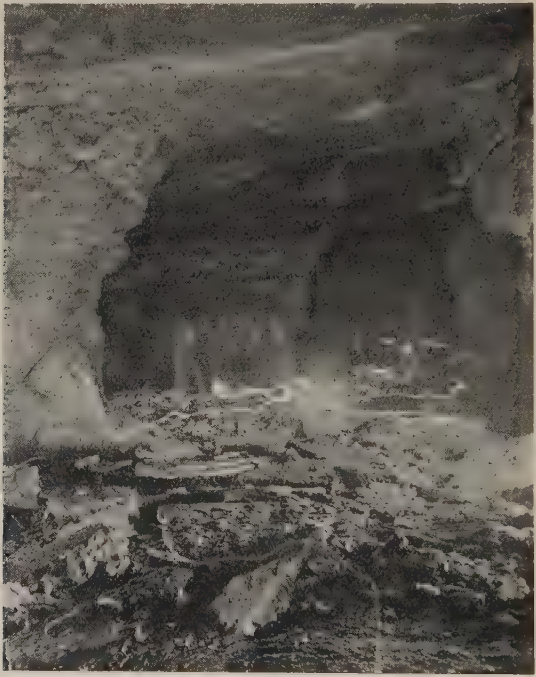

FIG. 233.—UNDERGROUND WORKINGS IN SILURIAN LIMESTONE,

at Rushall, near Walsall. The limestone is in part nodular and in part evenly bedded, and occurs between beds of shale: by courtesy of East Anglian Cement Co.

Bessemer's invention of a process for steel-making that favoure other types of ore, led to a decline in the use of the Coal Measur ores and their replacement by hæmatite iron ores; these were, fo the most part, imported, especially from Spain, although consider able quantities were and still are obtained in Cumberland and i the south of Glamorgan. In many cases, however, it was foun expedient to take the ore to the place where the coal and the limestone were available, and the centres of the industry remained unchanged although the local ores were no longer used.

Similarly, it was the association of coal, iron-ore, and limestone that led to the prominent part played by South Staffordshire in the early days of the iron industry, and the same combination, with the addition of grit-stone (for grinding) was responsible for the development of the cutlery industry around Sheffield.

A somewhat similar story could be told of the part played by limestone in the industrial development of North Wales. As we have already seen, and as is further illustrated in *Fig.* 231, the Carboniferous Limestone determined the location of many important masses and veins of ores containing lead and zinc, while it also contains hæmatite iron ores similar to those of Cumberland and the south of Glamorgan. The association of the ores with the materials necessary for their treatment is illustrated in *Fig.* 232.

The frequent association of limestone with argillaceous material suitable for cement making has already been referred to: the Lias limestones and the Wenlock Limestone are always associated with shales, while glacial deposits resting on limestone, alluvial muds where estuaries occur near the outcrop of the Chalk, and the marly character of some parts of the Chalk itself, have also determined the location of important cement works.

The foregoing are but a few of the innumerable instances of the relation between limestone and certain phases of industry, and sufficient has been written in previous pages to show that the same applies to the other commercial activities in which limestone plays a part, and also to show how sound were some observations concerning what we should now call geology, made by Dr. Robert Plot in his "*Natural History of Oxfordshire*" (1705). He wrote:—

> "I cannot but reprehend the petulant Despisers of this innocent sort of Learning, who in Derision have called it, picking of stones; as if what the Omnipotent and most Wise God hath thought fit to create, were not worth the Consideration of weak Man. But let such malicious Scoffers know, that 'tis their Pride and Ignorance that has engaged them in this Censure; for . . some things must be writen of meerly for Information, as well as others that tend to our Advantage. Besides, who knows but these things may have a Use, that hereafter may be discovered, though not known at present."

APPENDIX I.

THE CLASSIFICATION OF THE ANIMAL KINGDOM.

The following notes upon the classification of the members of th animal kingdom are included for those who may find it inconvenient to consult palæontological works in which fossils are discussed in greater detail.

There are nine principal subdivisions of the animal kingdom, each of which is known as a PHYLUM. Each phylum includes CLASSES of organisms that have certain features in common, and the classes are further subdivided into ORDERS and these in turn into FAMILIES.

Each family includes a number of GENERA and each genus is made up of SPECIES. The species is the unit of classification in the animal and plant kingdoms, and the term implies a group of individuals that are so closely alike as to make it highly probable that they descended from a common but not remote ancestor, while a genus may be regarded as a collection of species that possess certain features in common as a result of a common ancestry; but the precise significance of both terms is very difficult to define, and the separation of one species or of one genus from another is often very arbitrary.*

The name of a fossil (this applies also to living animals and plants) usually consists of two portions— in accordance with a practice introduced by the Swedish naturalist, Carl von Linné (or Linnæus): for example, a certain species of brachiopod is known as *Productus giganteus*: the name is made up of the generic name *Productus*, that signifies certain forms of brachiopod to the exclusion of all other brachiopods, and of *giganteus*—a trivial name that serves to distinguish the species from all the others that are included in the same genus.

Phylum PROTOZOA.—This phylum includes the simplest forms of animals. They are usually small and consist of one living cell only. Two Orders, the Foraminifera and the Radiolaria, occur as fossils, and members of the former group, although usually minute, contribute largely to the formation of limestone because they have a covering (often globular, flask-shaped or spiral, *Figs.* 142 & 228), usually consisting of calcium carbonate. They received their name because of the slender thread-like filaments that, proceeding from the body, pass through *foramina* or holes in the shelly covering. The Radiolaria (which are also minute) have a beautifully constructed framework of silica, and thus cannot contribute to the formation of limestone, although they probably produced some of the silica of chert and flint.

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* See Davies, A. M., "An Introduction to Palæontology," Murby & Co., London; Hawkins, H. L., "Invertebrate Palæontology," Methuen & Co., London; Neaverson, E., "Stratigraphical Palæontology," Macmillan & Co., London.

Phylum PORIFERA. — This group includes only one class, the sponges, in which the animal is a little more complex than in the protozoa. The body is traversed by tubes or canals (hence the name *porifera*, pore bearers) that convey the water from which the animal derives its food. They have a supporting framework which, if it consists of mineral matter, is in most cases of silica, and like the radiolaria the sponges have contributed to the materials of flint and chert. A few forms have calcareous skeletons, but the sponges have not been important limestone builders.

Phylum COELENTERA.—These received their name (hollow intestine) because the body of the individual animal or polyp has one cavity that communicates with the exterior by means of a mouth. In many forms, the individuals grow in close association and form large colonies. The Coelentera include the jellyfish, graptolites, and corals. The jellyfish are devoid of hard parts and are rarely preserved as fossils. The graptolites (from the Greek *grapho,* I write) are so called because of the resemblance of some forms to a quill pen. Their general characters are illustrated in *Fig.* 48, and although they are of great importance in determining the relative ages of the rocks in which they occur, they have not contributed to the formation of limestone, because the skeleton consisted entirely of horny matter. They became extinct before the end of Silurian times.

In the corals the soft body is supported by a cup-like or conical structure of calcium carbonate, divided and subdivided by radially arranged vertical plates (*Figs.* 71, 73, & 78). Sometimes the polyps lived a solitary existence, but in most forms they grew in close contact, building up massive skeletons (*Fig.* 49) which have at times been so abundant on the floors of shallow seas as to build up extensive "reefs." Corals have contributed largely to the formation of limestone, some varieties of which consist almost entirely of the well-preserved remains of their skeletal structures (*Figs.* 59 & 78).

Phylum ECHINODERMATA.—This great group of marine animals includes crinoids, starfishes, and sea-urchins. The bodies are generally protected by an armour of calcareous plates which often bear sharp movable spines : it is on account of the latter feature that the group received its name, from the Greek *echinos,* a hedgehog, and *derma,* skin. The crinoid (*Fig.* 22) may be described as a kind of many-branched starfish attached to a long stalk. The body is protected by a cup built up of stout calcareous plates, and the stalk consists largely of crystalline calcite (*Fig.* 23); on this account the crinoids, which are now almost extinct, have been very important as limestone builders in the past.

The starfishes lead a free existence and are not so heavily armoured as the crinoids. Many forms occur as fossils, but they have not contributed much to the formation of limestones.

The sea-urchins, which have a heart-shaped or globular shelly case, usually completely covered with spines (*Figs.* 117 & 150) are also abundant as fossils, especially in the Cretaceous and Oolitic limestones.

Phylum VERMES.—The vermes or worms are usually devoid of hard parts, but some marine members invest themselves in calcareous tubes which they attach to stones or empty shells on the sea floor. These tubes occur as fossils, and the creatures have, no doubt, contributed appreciably to the extraction of calcium carbonate from se water.

Phylum POLYZOA. — The polyzoa (or bryozoa) are small marin animals that live in colonies, the horny or calcareous supporting struc tures of which form plant-like tufts that adhere to shells and stones o the sea floor or give rise to compact somewhat rounded masses. Th group includes the modern "sea-mats." Although often found a fossils it is only occasionally that the polyzoa were sufficiently abundan to make important contributions to limestone formation.

Phylum BRACHIOPODA. — In this important class of marin animals there is an external covering consisting of two shells o "valves," one situated on the upper surface of the animal and one o the lower surface. The lower valve is usually somewhat larger than the upper, and, in many forms, it has, at one end, a hole for the passag of the fleshy stalk by means of which the animal attaches itself t stationary objects. In *Fig.* 69 the fossil is viewed from above, and th lower valve projects (at the top of the photograph) from beyond th edge of the upper valve. The brachiopods (from the Greek, *brachion* an arm) derive their name from the fleshy "arms" coiled up withi the shells and used for the purpose of wafting food particles to th mouth. In some forms the shell is thin and horny, but it usually consists of calcium carbonate.

The brachiopods were extremely abundant during Palæozoic and Mesozoic times, and contributed largely to the formation of limestone, some beds of which consist almost entirely of their shells, either whol or in fragments.

Phylum MOLLUSCA.—This group includes most of the so-called "shell fish," and of the five classes into which it is divided, three are very important as fossils and as limestone formers: they are (a) the Cephalopoda (from the Greek *kephalon*, the head, and *podos*, a foot), so called because the "feet" or tentacles by means of which the animals move about are situated in the neighbourhood of the head, or rather the mouth: *e.g.*, the nautilus, (b) Lamellibranchs (from the Latin *lamella*, a little plate, and *branchia*, gills) so called on account of the plate-like gills by means of which they breathe: *e.g.*, the oyster, (c) Gastropoda (from the Greek *gaster*, a belly, and *podos*, a foot) so called because the animal moves along on its abdomen: *e.g.*, the snail.

The Cephalopoda include *Nautilus*, the ammonites, the belemnites and the cuttlefishes. Of these, the last named, having little or no hard part capable of preservation are not important as fossils; the belemnites, an extinct group allied to the cuttlefishes had an internal calcareous shell known as a "guard," like a short stout rod, bluntly pointed at one end (*Fig.* 136); the ammonites and the nautiloids, the former of which are quite extinct, had external calcareous shells, usually coiled (*Figs.* 99, 116, 135 & 137), but sometimes straight (*Fig.* 64), and they played a very important part in extracting calcium carbonate from the sea water and "fixing" it as limestone: this is especially the case with the ammonites, which were extremely abundant both in kind and individuals during the Jurassic and Cretaceous Periods.

The Lamellibranchs, which include marine creatures like oysters and cockles, and freshwater creatures like *Unio* and the swan-mussel, have a calcareous shell consisting of two "valves," one placed on either side of the animal (*Figs.* 125 & 155) and hinged together by means of a more or less elaborate system of interlocking " teeth." They have been abundant since comparatively early Palæozoic times, and throughout a long period have been important secreters of calcium carbonate.

Gastropods (*Figs.* 11, 20, & 155) have a shell consisting of one piece in the form of a simple cone (the limpet) or a spirally wound cone (winkles and whelks), and they are very abundant as fossils: some limestones such as the Purbeck Marble consist largely of their remains. A few forms, including some of the slugs which have no shelly coverings, are not represented as fossils.

Phylum ARTHROPODA.—This comprehensive group includes the jointed-limbed animals (from the Greek *arthron*, a joint, *podos*, a foot) such as the insects, spiders, scorpions, crabs, lobsters and trilobites. Although many of the marine forms such as the three last named, have hard external coverings consisting partly of calcium carbonate, the arthropods have not contributed a great deal to limestone formation, although in some of the thin limestones of the lower Palæozoic strata (for example, parts of the Llandeilo Limestone) the remains of trilobites are so abundant as to constitute the bulk of the rock.

Phylum VERTEBRATA.—The vertebrates or back-boned animals include fishes, birds, amphibians (frogs), reptiles, and mammals, and although a skeleton in which calcareous salts play an important part is present in practically all members of the phylum, the vertebrates are not conspicuous as limestone formers. In the case of the birds, the land reptiles, and the mammals, even the chance of preservation as fossils has been remote, for only on rare occasions would the body of such an animal come to rest in the sediments accumulating on the floor of the sea or of a lake.

APPENDIX II.

ANALYSES OF LIMESTONES.

No useful purpose would be served by compiling an extensive series of the analyses of limestones that have from time to time been published, because, as a rule, the chemical composition of a limestone is of less importance than its physical properties, and when the composition *is* a vital factor, an analysis other than one specially made for the purpose in view is likely to be misleading.

Nevertheless, certain interesting features emerge from a study of the composition of the various kinds of limestone, and the following analyses culled from many sources, details of which are given on page 439, will serve to illustrate the chemical composition of the rock-group as a whole.

According to the purpose for which it was made, an analysis of a limestone may indicate merely the percentage of the principal ingredients, or it may give, also, information regarding constituents of minor importance: for comparative purposes it is necessary that all the results should be presented in the same form, and, therefore, the following analyses have been recalculated (where necessary) so as to show the relative abundance of the principal constituents of limestones and dolomites, namely, calcium carbonate and magnesium carbonate and of the most important impurities, namely, iron and alumina on one hand, and silica, together with other insoluble residues, on the other. The remaining ingredients, the proportion of which is indicated by the difference between the total given in each case and 100, include moisture, organic matter, and alkalies such as soda and potash; a few detailed analyses are given in order to indicate the nature of these relatively unimportant constituents.

It should be noted that some of the silica may occur as quartz (grains of sand that were present in the original sediment), but some will, in most cases, be combined with alumina in the form of clay, or (especially in the metamorphosed limestones) with other oxides, giving rise to complex silicate-minerals.

In the following tables "iron" means the combined total of the oxides of iron, Ferrous oxide (FeO) and Ferric oxide (Fe_2O_3), either or both of which may be present, in the free state or combined with carbon dioxide or with certain other oxides. Details relating to methods of analysis will be found in a Bulletin (700) of the United States Geological Survey ("The Analysis of Silicate and Carbonate Rocks").

Recently formed calcareous deposits and chalk.

	1*	2	3	4	5	6
Calcium carbonate	89.20	98.82	91.66	92.00	98.40	94.09
Magnesium carbonate ...	—	0.53	1.51	4.37	0.08	0.31
Iron and Alumina	0.40	0.06	0.20	0.56	0.42	1.29
Silica and Insoluble residues	4.60	0.05	4.03	0.25	1.10	3.61
	94.20	99.46	97.40	97.18	100.00	99.30

1. Tufa, Dursley, Gloucestershire.
2. Tufa, Mammoth, Hot Springs, Yellowstone, U.S.A.
3. Recent Oolitic Sand, Salt Lake, Utah, U.S.A.
4. Shell Sand, Key West, Florida, U.S.A.
5. Chalk with Flints, Shoreham.
6. Grey Chalk, Folkestone.

* The authorities for the analyses are given on page 439.

The Dursley Tufa, with its comparatively large amount of organic matter and moisture, should be compared with the Tufa deposited from the Yellowstone hot springs.

An interesting feature connected with the composition of the chalk is that silica is less abundant in the Upper White Chalk, in which flints occur, than in the Lower Grey Chalk from which they are absent. The bearing of this upon the origin of flints has already been discussed (see page 261).

The oolites.

	7	8	9	10	11	12
Calcium carbonate	95.16	79.0	96.01	94.52	97.88	77.6
Magnesium carbonate ...	1.20	3.7	1.18	2.50	—	—
Iron and Alumina	0.50	2.0	0.45	—	0.69	21.4
Silica and Insoluble residues	1.20	10.4	1.15	1.20	1.26	
	98.06	95.1	98.79	98.22	99.83	99.0

7. Portland Stone.
8. Chilmark Stone, Portlandian.
9. Lithographic Limestone, Solenhofn.
10. Great Oolite, Bath.
11. Upper Corallian Limestone of Malton, Yorks.
12. Grey Limestone (Lower Oolites), Maybeck, Yorks.

As in the case of the Chalk, there is great variation in the amount of silica that may be present in the oolitic limestones; in some cases t is present as grains of sand, an original constituent of the sediment, s would be expected in view of the shallow water origin of many of he rocks, and in other cases it is present as a siliceous cementing naterial subsequently deposited between the grains.

JURASSIC LIMESTONES, INFERIOR OOLITE AND LIAS.

	13	*14*	*15*	*16*	*17*	*18*
Calcium carbonate	95.89	93.59	94.35	84.55	86.00	80.0
Magnesium carbonate ...	0.11	2.90	3.35	—	2.00	0.3
Iron and Alumina	1.64	0.80	0.89	2.33	3.00	4.0
Silica and Insoluble residues	2.04	—	0.08	11.15	8.00	12.7
	99.68	97.29	98.67	98.03	99.00	97.0

13. Doulting Stone, Inferior Oolite.
14. Ancaster Stone, Inferior Oolite.
15. Weldon Stone, Inferior Oolite.
16. Lias Limestone, Pylle, Somerset.
17. Lias Limestone, Aberthaw, Glamorgan.
18. Lias Limestone, Kirton-in-Lindsey, Lincolnshire.

The limestones of the Inferior Oolite are generally rich in calcium carbonate and contain but little iron: there do not appear to be any highly magnesian varieties. The Liassic Limestones, as would be expected from their mode of origin, are rich in alumina and silica that represent argillaceous and sandy material present in the original sediments.

TRIASSIC AND PERMIAN LIMESTONES.

	19	*20*	*21*	*22*	*23*	*24*
Calcium carbonate	78.97	77.64	44.41	54.87	51.10	26.50
Magnesium carbonate ...	6.39	4.17	**31.85**	**43.07**	**40.20**	**17.98**
Iron and Alumina	0.71	6.17	2.95	0.73	1.80	1.32
Silica and Insoluble residues	13.31	11.13	19.87	0.56	3.60	51.40
	99.38	99.11	99.08	99.23	96.70	97.20

19. Limestone (Rhætic), Bridgend, Glamorgan.
20. Limestone (Triassic), Sully, Glam.
21. Dolomite (Triassic), Sully, Glam.
22. Magnesian Limestone (so-called Permian), Anston.
23. Magnesian Limestone (so-called Permian), Bolsover.
24. Siliceous Dolomite of Mansfield.

This group of analyses reveals the dolomitic character of many of the Triassic and Permian calcareous rocks. Silica is, on the whole, abundant, and the Mansfield stone, as already indicated, is really a sandstone with a dolomitic matrix.

CARBONIFEROUS LIMESTONE.

	25	26	27	28	29	30
Calcium carbonate	98.90	98.93	74.26	80.96	96.20	59.55
Magnesium carbonate ...	0.45	—	2.33	1.71	1.33	**31.00**
Iron and Alumina	0.25	0.18	0.37	15.46	1.51	9.14
Silica and Insoluble residues	0.75	0.36	21.84			
	100.35	99.47	98.80	98.13	99.04	99.69

25. Hopton Wood Stone, Derbyshire.
26. White Limestone, Benllech Cove, Anglesey.
27. Black Limestone, Benllech Sands, Anglesey.
28, 29, 30. From a group of connected quarries, Taff's Well, near Cardiff, illustrating possible variations.

The light coloured Carboniferous Limestones are, on the whole, very pure, but much silica is often present in some of the thin earthy limestones that are interbedded with shales, and organic matter is relatively abundant in the dark limestones.

Analyses 28-30 illustrate the extent to which the composition may vary in different beds in the same locality, and demonstrate the necessity for careful and continuous observation in cases where the chemical composition of the limestone is of importance. In other cases the composition may remain constant over a relatively large area and through a considerable thickness of strata.

CARBONIFEROUS AND OTHER DOLOMITES.

	31	32	33	34	35	36
Calcium carbonate	58.49	54.12	53.79	55.70	52.82	54.35
Magnesium carbonate ...	**37.85**	**34.02**	**43.61**	**38.85**	**43.74**	**45.65**
Iron and Alumina	2.26	7.66	2.05	4.83	0.40	—
Silica and Insoluble residues	1.59	0.21	0.87	0.60	3.24	--
	100.19	96.01	100.32	99.98	100.20	100.00

31. Carboniferous, Cefn On, near Cardiff, average of six.
32. Carboniferous, Penrhyn-y-gell, Anglesey.
33. Carboniferous, near Penmon, Anglesey.
34. Carboniferous, Clydach, near Abergavenny.
35. Knox Dolomite, Alabama, U.S.A.
36. Composition of ideally pure Dolomite.

Although closely approached, the composition of chemically pure dolomite is never attained in nature, for there is always a preponderance of calcium carbonate in dolomitic limestones.

It is interesting, in view of the association of dolomitic limestone with iron ores in the Carboniferous Limestone, to note the relative abundance of iron in the dolomitic varieties of that rock: this would also be suspected from the frequency with which such limestones exhibit tints of red and yellow.

DEVONIAN AND SILURIAN LIMESTONES.

	37	38	39	40	41
Calcium carbonate	94.00	57.80	69.30	88.89	60.80
Magnesium carbonate	0.80	**39.70**	—	3.69	**28.30**
Iron and Alumina	3.30	0.60	9.40	5.38	8.40
Silica and Insoluble residues	1.90	1.90	19.50	1.48	0.40
	100.00	100.00	98.20	99.44	97.90

37. Devonian Limestone.
38. Devonian Dolomite.
39. Cornstone (Old Red Sandstone), Milford Haven.
40. Wenlock (Silurian) Limestone, Coed-y-Paen, Monmouthshire.
41. Wenlock (Silurian) Limestone, May Hill, Gloucestershire.

The Devonian Limestones include dolomites and calcareous varieties, while the Silurian Limestones are, on the whole, somewhat argillaceous, and are rarely as dolomitic as that represented by the analysis in Column 41.

PRE-CAMBRIAN LIMESTONES AND CERTAIN METAMORPHIC MARBLES.

	43	44	45	46	47
Calcium carbonate	52.16	89.54	99.24	90.69	61.95
Magnesium carbonate	4.66	0.31	0.28	—	**34.04**
Iron and Alumina	5.51	2.01	0.29	0.53	0.21
Silica and Insoluble residues	37.60	4.96	—	8.00	2.46
	99.93	96.82	99.81	99.22	98.66

43. Pre-Cambrian Limestone, Rhos-Mynach-isaf, Anglesey.
44. Pre-Cambrian Limestone, Bodwrog, Anglesey.
45. Carrara Marble.
46. White Marble, Rutland, Vermont, U.S.A.
47. Dolomite Marble, Natal.

The Pre-Cambrian Limestones present variations in composition similar to those seen in limestones of later formations; some are very pure, some are dolomitic, and others are highly contaminated with argillaceous and sandy material. Owing to the extent to which the rocks have suffered metamorphic action, the magnesia, alumina, and silica, are probably for the most part present as complex silicate-minerals.

The Carrara statuary marble, as would be expected from its whiteness, is remarkably pure, and it must have been derived from a limestone as free from earthy material as the purest portions of the White Chalk.

SOME DETAILED ANALYSES.

	49	50	51	52	53	54
Lime, CaO	42.61	38.46	53.65	53.55	29.24	54.60
Magnesia, MgO	7.90	5.73	0.32	0.32	19.49	0.68
Carbon dioxide, CO2 ...	41.58	32.24	42.26	42.04	43.94	42.70
Oxides of Iron, FeO; Fe_2O_3	0.54	1.30	0.72	1.22	1.68	0.27
Alumina, Al_2O_3	0.81	4.32	0.31	0.46	—	0.10
Silica, SiO_2	5.19	12.41	0.93	0.42	3.64	1.60
Titanium dioxide, TiO_2 ...	0.06	0.32	—	—	—	—
Manganese oxide, MnO ...	0.05	0.04	—	—	trace	—
Potassium oxide, K_2O ...	0.33	2.60	—	—	—	—
Sodium oxide, Na_2O	0.05	1.34	0.38	0.44	—	—
Phosphorus pentoxide, P_2O_5	0.04	0.04	—	—	—	trace
Sulphur, S	0.09	—	—	—	—	—
Sulphur trioxide, SO_3	0.05	—	0.11	trace	—	.035
Iron sulphide, FeS_2	—	0.25	—	—	—	—
Chlorine, Cl.	0.22	—	—	0.03	—	—
Water, H_2O	0.77	0.93	0.74	0.88	0.46	—
	100.09	99.98	99.42	99.36	98.45	99.985

49. Average of 345 Limestones.
50. Marble, Tiree, Argyllshire.
51. Inferior Oolite, Dundry.
52. Great Oolite (Bath Stone).
53. Magnesian Limestone, Bolsover Moor, Derbyshire.
54. Carboniferous Limestone, Trefil, near Tredegar, S. Wales.

It will be noticed that, as a rule, ingredients other than those that may be regarded as essential constituents of limestone and dolomite are present in very small proportions, if at all. The somewhat peculiar composition of the Pre-Cambrian limestone (Column 50), which is a crystalline marble, is probably to be attributed to contamination by igneous rock during the process of metamorphism.

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APPENDIX III.

Table showing output of limestone and chalk in Great Britain from 1895-1926.

	1895-1913	1921	1922	1923	1924	1925	1926	1923-26
Limestone								
England, including Isle of Man	Average of 19 years (1895-1913) before the war.	5,751,369	7,359,804	8,715.512	9,916,440	10,180,825	8,537,173	Average 1923-26 after the recovery from the 1920 strike.
Wales		1,296,151	1,825,945	2 386,815	2,257,212	2,638,451	2,259,393	
Scotland		193,096	272,929	329,185	319,819	241,477	222,313	
Total of limestone for Great Britain	11,867,215	7,340,616	9,814,678	11,431,552	12,813,471	13,060 753	11,018,779	12,081,139
Chalk								
England and Wales ...	4,355,046	3,346,210	3,024,448	3.593.354	4,402,560	5,035,350	4,314,707	4,336.493
Total of limestone and chalk for Great Britain	16,222,261	10,686,826	12,839,126	15,024,906	17,216,031	18,096,103	15,333,486	16,417,632

The above figures, extracted from the Annual Reports of the Secretary for Mines, show that apart from the effect of the industrial dispute in 1920, the average annual output of limestone has been remarkably constant for many years, as will be seen on comparing the average for 1895-1913 with that for 1923-6. The Reports of the Secretary for Mines for recent years give also details of the output from each county and the uses to which the rock has been put, and they should be consulted by those in search of statistical details.

APPENDIX IV.

SOME PHYSICAL PROPERTIES OF LIMESTONE.

The following details relating to the crushing strength and relative weight of certain important limestones have been extracted to a large extent from a paper on the "Building Stones of Great Britain: their crushing strength and other properties," by T. A. Beare, in the *Proceedings of the Institute of Civil Engineers,* Vol. 107 (1892), from A. R. Warnes' "Building Stones, their properties, decay and preservation" (London: Ernest Benn, 1926), and from information published by quarry owners.

	Crushing load in tons per square foot.	*Density.*	*Weight of a cubic foot in pounds.*
CHALK.			
Beer Stone	162.1	2.12	131.7
Clunch	72 0	2.13	133.0
Totternhoe Stone	124.0	1.86	166.0
UPPER OOLITES.			
Chilmark Stone	136.6	2.48	154.0
Portland (Base Bed)	287.0	2.20	137.6
,, (Whit Bed)	204.7	2.10	132.3
GREAT OOLITE SERIES.			
Caen Stone	198.0	2.70	168.0
Corsham Down Stone	94.5	2.06	129.0
Farleigh Down Stone	62.5	1.93	120.5
Monks Park Stone	139.6	2.19	136.7
Box Ground Stone	97.5	2.05	127.9
Coombe Down Stone	117.7	2.06	128.6
Stoke Ground Stone	90.0	2.03	126.3
Winsley Ground Stone	100.7	2.13	132.9
INFERIOR OOLITE SERIES.			
Doulting Stone	103.9	2.0	125.0
Ham Hill Stone	166.3	2.18	136.0
Ham Hill Grey Bed	259.0	2.25	140.0
Leckhampton Stone	201.0	2.23	139.0
Ancaster Free Stone	184.0	2.25	140.4
Ancaster Weather Stone	552.6	2.50	156.3
MAGNESIAN LIMESTONE SERIES.			
Anston Stone	301.9	2.12	132.2
Parknook Stone	487.0	2,44	151.5
Roche Abbey Stone	250.0	2.23	139.0
Huddlestone Stone	278.0	2.21	137.5
Mansfield Red Stone	591.9	2.29	143.2
,, White Stone	461.7	2.25	140.1
,, Yellow Stone	577.4	2.33	145.4

	Crushing load in tons per square foot.	*Density.*	*Weight of a cubic foot in pounds.*
CARBONIFEROUS LIMESTONE.			
Hopton Wood Stone	806.0	2.54	158.0
SANDSTONE.			
Forest of Dean Stone	530.0	2 42	151.4
Craigleith Stone	861.9	2.22	138.6
GRANITE.			
Cornish Grey	959.9	2.59	161.7
Peterhead	1207.7	2.54	158.5

The crushing load given is usually the mean of several tests.

It is not possible to base any important conclusions upon a series of figures such as that given above, but it will be noticed that in general, as far as the limestones are concerned, a high resistance to crushing is accompanied by a high relative weight, and that the crushing strength tends to increase with the age of the rock. Figures relating to certain sandstones and granites are given for comparison.

APPENDIX V.

SOME ADDITIONAL NOTES

mainly relating to information received while this book was passing through the Press.

Chapter I., page 15. *Plants and calcareous waters.—Chara* grows readily in " hard " waters, and on this account frequently gives trouble in reservoirs storing water derived from limestone. It has been calculated that in some cases the growth of *Chara* has reduced the hardness of water by 2°, but it leads to organic contamination. Its growth has been temporarily stopped by cementing the bottoms of affected reservoirs. [See L. Richardson, " Wells and Springs of Gloucestershire," *Memoirs of the Geological Survey*, 1930, and J. H. Garrett, in *Transactions of the Institute of Water Engineers*, Vol. 17 (1912), pp. 172-3.]

Chapter II., page 33. *Limestones of algal origin.*—More details relating to the recent algal limestones of Australia have been made available by the publication of Sir Douglas Mawson's paper [" Some South Australian Algal Limestones in Process of Formation," *Quarterly Journal Geological Society*, Vol. 85 (1929), pp. 613-623]. In one part of the area, where there is a covering of shallow water during the wet season but a dry surface in the summer, the ground is strewn with round plates of limestone ranging from tiny particles to discs eight inches in diameter. When placed in acid the calcium carbonate dissolves and the residue is a brownish slimy material, retaining, more or less, the shape of the original disc or " biscuit " and consisting of the macerated remains of algæ. " Lake-balls " consisting of algæ have long been known; they were recorded in 1886 in a lake in the Shetland Islands [G. W. W. Barkley, " On some Algoid Lake Balls from South Uist," *Proceedings Royal Society, Edinburgh*, Vol. 13 (1886), p. 845], but as the water contained little or no calcium carbonate they were not calcified. In Lough Belvedere in Ireland, however, the composition of the water is such that algal masses are represented by calcareous pebbles, and similar occurrences have been recorded from other parts of the world, all associated with the activities of blue-green algæ. The reason for the deposition of the calcium carbonate is, of course, that during the process of growing the algæ extract carbon dioxide from the water; and since it is by reason of the presence of that gas that the mineral matter is held in solution as the relatively unstable calcium bicarbonate, its removal breaks up the calcium compound, precipitating the normal carbonate which is almost insoluble.

The limestone "biscuits" of South Australia evidently represent colonies of algæ that extract calcium carbonate, in which the water is particularly rich, and that, during the summer, when the pools dry up, become hard. The algal growth is, however, not terminated, but only arrested until the return of favourable conditions, because, when placed in water, the plants recommence to grow from the desiccated spores that are attached to the surface of the "biscuit."

CHAPTER III., page 63. *Relative abundance of limestone in the earth's crust.*—It should be borne in mind that on account of their mode of formation, sedimentary rocks tend to be more widely distributed at the earth's surface than those of igneous origin, but, taking the outermost layers of the earth's crust into consideration, sedimentary rocks can only constitute about 5 per cent. of the whole. F. W. Clarke and H. S. Washington ["The Composition of the Earth's Crust," *United States Geological Survey,* Professional Paper, 127] have estimated that the relative abundance of the various classes of rocks in the outermost ten miles of the earth's crust is as follows:—

Igneous rocks	95.00 per cent.
Argillaceous rocks (clays and shales)	4.00 per cent.
Arenaceous rocks (sandstones and conglomerates)	0.75 per cent.
Calcareous rocks (limestones)	0.25 per cent.

CHAPTER VII., page 129. *Uplift and sub-aerial erosion during Carboniferous Limestone times.*—That during, or just after, the deposition of the Carboniferous Limestone, some districts were elevated to such an extent that the surface was subjected to atmospheric weathering, producing an uneven surface on which shallow water deposits accumulated, is also indicated in a number of localities in South Wales. For example, at Pendine in Carmarthenshire, the series includes a layer of limestone lumps enclosed in a sandy matrix, and the characters and relations of the bed indicate that it was formed as a result of subaerial weathering in Carboniferous Limestone times. Above the conglomeratic layer there is a bedded limestone, the top of which is even, while the bottom is undulating, owing to the irregular character of the surface upon which it was deposited [see "The Country around Carmarthen," *Memoirs of the Geological Survey* (1909), p. 81].

At Haroldston St. Issels in Pembrokeshire the Millstone Grit rests on an uneven surface of Carboniferous Limestone, and there are, in the upper layers of the limestone, isolated patches of grit which obviously represent material deposited in cavities produced by solution during a period of sub-aerial weathering that immediately preceded the deposition of the Grit [see "The Country around Haverfordwest," *Memoirs of the Geological Survey* (1914), p. 151].

Mr. E. E. L. Dixon has shown that, at Ifton in Monmouthshire, the relation between the Carboniferous Limestone and the Millstone Grit indicates that the former was sub-aerially eroded before the deposition of certain sandstones which are the local equivalents of the latter, and that the strata belonging to the topmost zone (the *Dibunophyllum* Zone) were completely worn away, while in those of the underlying *Seminula* Zone, deep channels, irregular caverns, and pipe-like fissures of unknown depth were formed by the solution of the rock ["The Unconformity between the Millstone Grit and the Carboniferous Limestone at Ifton, Mon.," *Geological Magazine*, Vol. 58 (1921), pp. 157-164].

Similar conditions—grit-filled, water-worn cavities in the top of the limestone beneath the Millstone Grit—also occur near Brynmawr at the north-eastern corner of the South Wales Coalfield [F. Dixey and T. F. Sibly on "The Carboniferous Limestone Series on the South-Eastern Margin of the South Wales Coalfield," *Quarterly Journal Geological Society*, Vol. 73, p. 161].

Chapter VII., page 133. *Cleistopora Zone.*—It has recently been shown [L. B. Smyth, *Scientific Proceedings Royal Dublin Soc.*, Vol. 18 (1927), pp. 423-431] that the coral hitherto regarded as the zone-fossil of the *Cleistopora* Zone belongs not to the genus *Cleistopora* but to *Vaughania*, Garwood. At present, however, the term *Cleistopora* Zone is still in general use.

Chapter VII., page 175, and Chapter X., page 218. *Shallow water types of Carboniferous Limestone, and some recent calcareous deposits.*—In the Bristol district, Belgium, and elsewhere, the Carboniferous Limestone includes what may be called *desiccation breccias*, which appear to be due to the drying up of the surface of a newly consolidated bed of calcareous material, followed by (a) the sinking of the resulting fragments into the still unconsolidated calcareous mud beneath, or (b) their enclosure in limy mud subsequently deposited upon the broken surface [S. H. Reynolds on "Breccias," *Geological Magazine*, Vol. 65 (1928), p. 101].

Professor H. de Dordolot has proposed the term *calcaire grumeleux* for similar breccias found in the Carboniferous Limestone of Belgium [A. Vaughan on "Correlation of Diantian and Avonian," *Quarterly Journal Geological Society*, Vol. 71 (1915), p. 26], and somewhat similar material is also seen in the Lias of Sedbury and Aust Cliff (where the so-called "Crazy Cotham Stone" is a kind of conglomerate formed by the contemporaneous breaking up of argillaceous limestone like the landscape marble) and in the Purbeck Limestone of the Dorset coast [A. Vaughan on "The Lowest Beds of the Lower Lias at Sedbury Cliff," *Quarterly Journal Geological Society*, Vol. 59 (1903), pp. 396-8].

What appear, especially on weathered surfaces, to be breccias (different from the *desiccation* breccias just described) occur in other parts of the Carboniferous Limestone, but always in beds that are (from other characters) considered to be of shallow water origin. The rock has the appearance of material that has been crushed into angular fragments and re-cemented, but the fact that it is limited to one horizon and is interstratified with normal limestones suggests that the condition is due to the mode of formation and not to subsequent crushing like that which has given rise to many brecciated marbles.

The matrix between the more or less angular fragments has often served as paths for dolomitisation ["The Country Around Swansea,' *Memoirs of the Geological Survey* (1907), p. 10].

Mr. E. E. L. Dixon, who called the rock "pseudobreccia," suggested that the character was due to patchy recrystallisation of the calcite in a calcareous mud, by reason of which the clayey and ferruginous matter has been concentrated in the matrix leaving the "fragments" relatively free from impurities [" The Carboniferous Succession in Gower (Glamorganshire) with Notes on its Fauna and Conditions of Deposition," *Quarterly Journal Geological Society*, Vol. 67 (1911), pp. 477-571].

Interesting light has been thrown upon the origin of " desiccation breccias," " pseudobreccias," and, indeed, of shallow water calcareous deposits in general, by a recent study of the reefs of the Great Bahama Bank [see M. Black, *Discovery* (March, 1930), pp. 75-78], and it would seem that many of the problems relating to limestone formation will be explained when that region has been thoroughly explored. Owing to its position and geographical relationships the water is shallow and is free from land-derived sediments, so that practically all the deposit now accumulating is calcareous, but it is not derived from the activities of corals, nor, to any great extent, from the shells of molluscs. There are large areas covered by white chalky mud known as *drewite*, after G. H. Drew, who suggested that the material was laid down as a result of the activity of certain bacteria, and there are also sands consisting largely of calcareous grains (in some respects resembling ooliths, but with a relatively much larger nucleus than in the average oolith of an oolitic limestone) and ground up shells. The " rock " of the islands has all the characteristics of a wind-blown deposit and consists of material similar to the calcareous sands, more or less consolidated.

The drewite consists principally of minute needle-shaped crystals of aragonite, with sponge spicules, foraminiferal shells, and minute fragments of the skeletons of other marine animals, and it throws light upon the origin of the desiccation breccias and pseudobreccias, which, as we have already seen, are associated with shallow water limestones.

For example, where tracts of drewite have been left dry as a result of slight elevation, the surface layers of the partly consolidated material have broken up along cracks, providing a kind of conglomerate or breccia, resembling the " desiccation breccias " and the calcaire grumeleux of the Carboniferous Limestone, and the " Crazy Cotham " of the Lias, while there are also layers still beneath the sea in which a patchy recrystallisation is producing a structure suggestive of that seen in the " pseudobreccias " of the Gower coast.

There are, in the calcareous mud, hard lumps consisting of finely crystallised calcite, rather more transparent than the unconsolidated drewite, apparently the result of local recrystallisation, and when the remainder of the material is also recrystallised, the product will have much in common with the pseudobreccias. Possibly it is the change from aragonite to calcite that is responsible for the recrystallisation and consolidation of the material, but there is not at present sufficient evidence to show exactly when, or how rapidly, the change takes place. It only affects the material of the more deeply buried layers because the aragonite crystals are stable so long as they are in contact with the sea water, from which it would appear that the " pseudobrecciation " proceeds as the thickness of the deposit increases.

Chapter IX., page 196. *Nodular limestones.*—It has been suggested that in some cases nodular limestone masses may have resulted from the partial solution, along joints or planes of bedding, of once continuous beds of limestone [F. Rutley, " On the Dwindling and Disappearance of Limestone," *Quarterly Journal Geological Society,* Vol. 49 (1893), pp. 372-384].

Chapter X., page 213.—Although by some writers regarded as belonging to the Great Oolite Series, the Guiting Stone has been shown to be a member of the Inferior Oolite Series, and it is so described in a recent Memoir of the Geological Survey [" The Country round Moreton in Marsh " (1929)].

The *Yellow Guiting Stone* of the North Cotteswolds is the local equivalent of the Pea-grit, while the *White Guiting Stone* of Temple Guiting represents the Lower Freestone. The former does not fade, and can be obtained in large blocks. Its good weathering properties are well illustrated in many local buildings.

Chapter X., page 215. *Jurassic stone-tiles.*—According to a recent Memoir of the Geological Survey [" The Country around Moreton in Marsh " (1929)] the Stonesfield Slate mines are in very active work, and the demand exceeds the supply. Deal pegs are now generally used for fixing the " slates ": oak was formerly employed, but it is found that when the peg is driven in, deal gives a better " head " than oak, and fewer slates are broken during fixing.

In the case of the Collyweston slates, the men employed in quarrying and splitting the material also act as " tilers " for fixing the slates.

Thick and heavy tilestones occur in the Chipping Norton Limestone (see p. 208), but they are not now worked to any extent.

Chapter X., page 222. *The climate of Jurassic times.*—It has already been noticed that shallow-water limestones accumulate most freely in warm regions, and since the general aspect of the flora and fauna of Jurassic times suggests that at *that* period the area with which we are concerned enjoyed a warm climate, it is not unreasonable to assume that therein lies the reason for the comparatively great development of shallow water limestones in the middle and upper parts of the Jurassic rocks. There are reasons for supposing that a careful correlation of past climates with phases of limestone-forming maxima would yield interesting results, but such a comparison is outside the scope of the present book. The climates of the past are discussed by C. E. P. Brooks in " Climate through the Ages " (1926), Ernest Benn, Ltd., London.

Chapter X., page 236, and Chapter XVII., page 418. *Jurassic limestones as roadstones: importance of research in roadmaking.*—In Oxfordshire, roads used to be made with the local oolitic limestones, which, being very soft, tended to give rise to creamy mud in winter and clouds of dust in summer, and were, apparently, quite unsuitable for roads intended to convey present-day heavy traffic. No better stone was obtainable locally, but in recent years the County Surveyor found that the oolitic limestone had much in common with the limestone " skeleton " of some of the rock-asphalts that are so well known as road-making media (see page 418). As a result of experimental tests, local oolitic limestone, impregnated with bitumen, was employed after the fashion of tar-macadam for making roads, and it has proved successful in regard to resistance to traffic and to weather, as well as in its lasting properties [see A. Lancaster Smith, " Cement, Lime and Gravel " (Vol. 4), January, 1930, p. 24, and " Modern Roadmaking," by H. Bradley and C. C. Hancock].

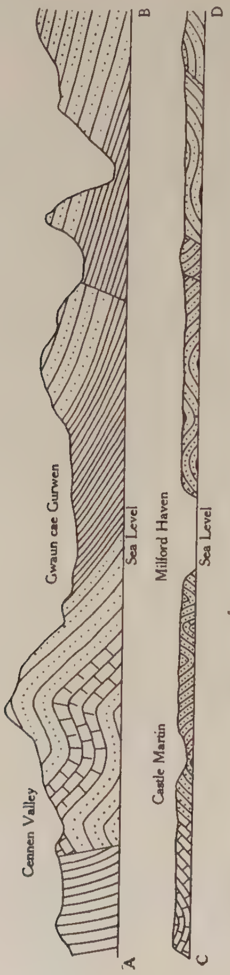

FIG. 234.—Sections across regions in South Wales illustrating the effects of marine denudation and sub-aerial erosion.

The action of the sea on a slowly subsiding or stationary land mass tends to produce an even surface as in the lower section CD, but except in its latest stages, sub-aerial denudation tends to the development of an uneven surface (as in Section AB) where the geological structure is such that rocks with varying degrees of resistance to erosion are exposed.

Chapter XI., page 254.—The use of *Beer Stone* is not confined to internal decoration, and it has been successfully used for external work especially, but not exclusively, in the south-west of England. Elaborately carved interior decorations are to be seen in many ecclesiastical buildings, for example, Hawkesyard Priory; Catholic Church, Exeter; and the Cathedral at St. Louis, Missouri, U.S.A.

Chapter XII., page 276.—The difference between the level surface resulting from marine erosion and the uneven surface produced when sub-aerial erosion is in active progress is illustrated in *Fig.* 234.

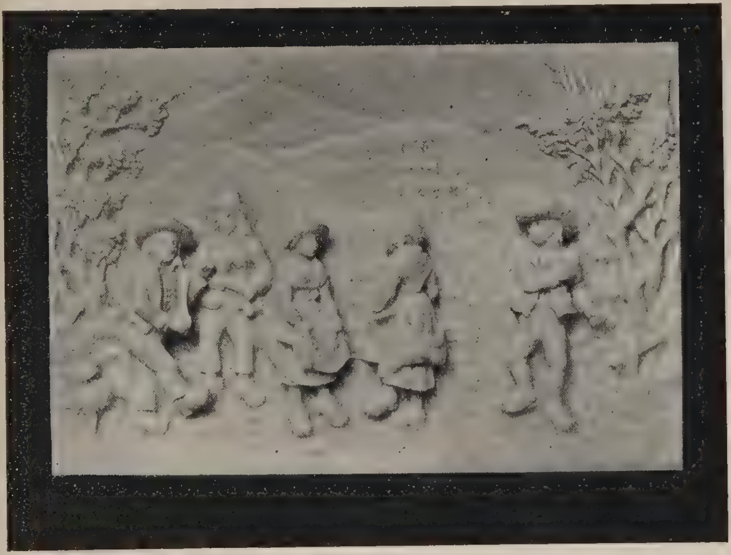

FIG. 235.—A natural cast in limestone.

Reproduction of a bas-relief made by allowing spring water highly charged with calcium carbonate to flow over a gutta-percha mould (from Clermont Ferrand, Auvergne, France); about natural size.

Chapter XII., page 299. *"Petrifying" springs.*—Much greater use is made of the "petrifying" character of many of the springs in the Auvergne district of France than is the case with those found in this country. The water holds in solution a very large amount of carbon dioxide, and is, therefore, rich in the carbonates of calcium and iron; and since, on reaching the surface, the gas tends to pass off rapidly, the mineral matter is quickly deposited. After being conducted through pipes filled with shavings and twigs upon which is deposited most of the carbonate of iron, the water contains practically nothing but calcium carbonate and is made to descend, cascade fashion, over a series of shelves upon which are placed the objects it is desired to "petrify." As in the case of the Knaresborough and Matlock springs, the process is not really one of petrifaction because the objects are merely crusted with a covering of mineral matter. In addition to the "nests" and other objects that can only be regarded as curios or souvenirs, the workers produce cameos and bas-reliefs of real Auvergne artistic value (see *Fig.* 235) by causing the calcium carbonate to be deposited in gutta-percha or sulphur moulds taken from well executed carvings. The objects so produced have the appearance of ivory [see account of an excursion to the Auvergne, *Proceedings Geologists' Association, London,* Vol. 17 (1902), p. 275].

Chapter XII., page 300. *Formation and rate of growth of stalactites.*—The process of stalactite formation is probably not quite as simple as the generally accepted explanation would suggest. If the deposition of the calcareous matter depended entirely upon the influence of the carbon dioxide that rain water derives from the air, it is unlikely that, when the water drips from the roof of a cave, the gas would be given off to such an extent as to result in the formation of important calcareous deposits. Emeritus Professor C. Thompson, of Cardiff, has suggested to me that, when passing through the soil, in which carbon dioxide is much more abundant than in the air, water takes up a quantity of that gas greatly in excess of what it can hold under atmospheric conditions: this increases its capacity to dissolve calcium carbonate, and, on reaching a cavity such as a cave in which the composition of the air is probably very similar to that of the outer air, the excess of carbon dioxide is given off with comparative rapidity, with a correspondingly rapid deposition of calcium carbonate.

At first a stalactite forms as a tube, because the deposition of material takes place round the edge of a drop that hangs from the roof of the cave, but the tube eventually becomes solid by the deposition of material within, and increases in diameter by the deposition of material without. The material in its original condition is soft and porous, but if it remains saturated with calcareous water, the pores become filled with crystalline calcite, the crystals of which are slender prisms radiating from the central axis of the stalactite. There is thus a concentric structure due to the mode of growth of the column, and a radial structure due to the recrystallisation of its material.

Very little is known concerning the rate of growth of stalactites. The North Bridge, Edinburgh, was erected in 1772, and after a century, stalactites an inch and a half in diameter, with the characteristic crystalline structure were found pendant from it, while in the Ingleborough Cave, Boyd Dawkins found the rate of growth to be .2946 inches per annum or nearly 30 inches in a century. This was believed to be an exceptionally rapid rate of growth ["On the Action of Carbonic Acid on Limestone," *Report British Association* (1880), p. 573]. In any case the present rate of growth in a cave like those at Cheddar or in Derbyshire is not necessarily an indication of the length of time that the pendant columns have taken to reach their present dimensions, for at times when the local water level was higher than it is now, the amount of mineral-charged water passing through the fissures may have been greater.

Chapter XIII., page 314. *Limestone scenery.*—The bare level surfaces of limestone, developed where the beds are horizontal, are well displayed in the North of England, especially in West Yorkshire, where they are known as *clints;* see *Fig.* 236. This illustration (reproduced from a paper on "Limestone Scenery" by Professor S. H. Reynolds in the *Proceedings of the Bristol Naturalists' Society,* 1929, pp. 114-119) shows also the deep fissures (sometimes called *grikes*) resulting from the widening by solution of vertical joints in the rock.

The fissures are often sufficiently deep and wide to make it difficult and even dangerous to traverse the limestone outcrop, and the accumulation of soil in the fissures is responsible for the somewhat unexpected appearance of solitary trees and bushes arising from the bare rock platform. Similar features are displayed where the Carboniferous Limestone occupies the ground at the foot of Ingleborough.

Chapter XIII., page 331.—In general, the fertility of the soil on the oolitic outcrops is related to its depth and to the amount of brashy material it contains. In common with other calcareous soils, those in the oolite country often tend to lose their organic matter by decay rather rapidly, and so need liberal manuring to make up the deficiency.

Chapter XIII., page 336. *Lime and honey-production.*—Some interesting observations made recently by Mr. W. O. Jones, secretary of the Glamorgan Beekeepers' Association, upon the relation between lime and honey-production are worth recording here. Noticing that, in Glamorgan, the production of honey was greatest on the outcrop of the Lias in the southern part of the county, experiments were conducted with a view to discovering what, if any, was the relation between honey-production and the composition of the soil. For this purpose, three areas were chosen where clover and lime trees were established, namely, (1) between Aberthaw and Llancarvan, on the outcrop of the Lower Lias (limestone and shale), (2) north of Cardiff (on the outcrop of the Old Red Sandstone where possibly the surface waters derived some lime from the Carboniferous Limestone that lies geographically above, and (3) between Treforest and Llantrisant, on the outcrop of Coal Measure sandstones, devoid of lime. In each case, eight plants of white clover and eight sprays of blossom on well-established lime trees were selected for treatment. On three successive days the blooms were covered with gauze to prevent visits by insects, whose work was imitated artificially. Tiny pointed tongues of blotting paper (dried and weighed) were used to soak up the nectar from each open floret, and the stamens were touched by the "tongues" held in silver forceps. It was found that the yield of nectar for the three areas was (1) 11 grains, (2) 5 grains, and (3) 4½ grains, respectively.

The experiments were carried out in places where no manurial rectification had been undertaken, and suggests the superiority, from the beekeeper's point of view, of plants grown on lime-bearing soils.

Of even greater importance is the discovery that the yield in the second area proved to be practically equal to that in the first, after suitable soil treatment including the application of lime in winter or basic slag (which contains lime) in spring.

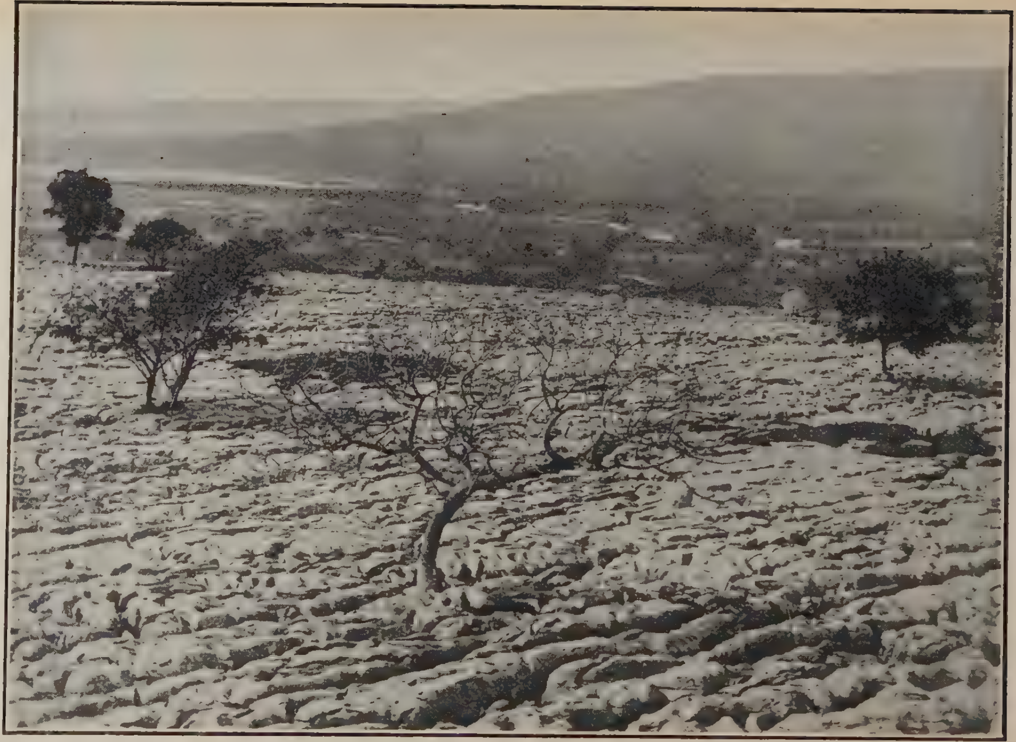

FIG. 236.—LIMESTONE SCENERY IN YORKSHIRE.

The Carboniferous Limestone occurs in horizontal beds, and weathering has resulted in the development of a bare level surface (clint) intersected by deep fissures (grikes): near Chapel le Dale, West Yorkshire. Reproduced by courtesy of Professor S. H. Reynolds and the British Naturalists' Society

Chapter XIV., page 351. *Water from Jurassic rocks.*—The abundance of tufa associated with springs that derive their supplies from rocks like the Inferior Oolite shows that the water readily deposits its calcium carbonate. Very pure at the time of its issue, the water seems prone to the development of organic growths, and this results in deterioration if stored in open reservoirs, for the water may become quite unfit for drinking purposes.

The Fuller's Earth, by throwing out the water that collects in the Great Oolite has determined the existence of many villages and farms, and but for that rock-division it is probable that most of the uplands of the Cotteswold region would have been uninhabited: see L. Richardson, "Wells and Springs of Gloucestershire," *Memoirs Geological Survey,* 1930.

Chapter XV., page 381.—In a recent paper J. A. Howe [*Journal of the Royal Institute of British Architects,* Vol. 37, 3rd Series (Nov. 9th, 1929), pp. 16-22] emphasises the value of washing buildings with pure water in order to remove soluble salts, that may, by their recrystallisation, disintegrate the surface layers of the stone. Such washing prevents decay under a film of dirt and increases the amount of light reflected from the stone: this paper contains special reference to buildings of Portland Stone.

Chapter XVI., page 406. *The manufacture of plaster of Paris.*—In some new American plaster works the process of grinding and calcining are accomplished in one operation. The grinding mill is surrounded by a suitable firebox heated by oil, gas, or powdered fuel, and the calcined plaster is removed by a mill-fan. There are also plants for preparing plaster from the calcium sulphate produced during the manufacture of hydrofluoric acid by the action of sulphuric acid upon the mineral fluorspar [R. M. Santmyers and J. Middleton, *Report of the United States Department of Commerce:* see also "The Quarry," Vol. 37 (March, 1930), pp. 96-9].

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